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FUEL CELL TECHNOLOGY PROGRAM

Final Report

Contract NAS 9-11033

Data Item No. 35



Prepared for

National Aeronautics and Space Administration
Manned Spacecraft Center
R and D Procurement Branch
Houston, Texas 77058

DIRECT ENERGY CONVERSION PROGRAMS

AIRCRAFT EQUIPMENT DIVISION
LYNN, MASSACHUSETTS

GENERAL  ELECTRIC

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FOREWORD

This report summarizes the results of a solid polymer electrolyte fuel cell development program conducted for the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, by the General Electric Company, Direct Energy Conversion Programs, Lynn, Massachusetts, under Contract NAS 9-11033.

The objective of this program was to advance the technology for a cost-effective hydrogen/oxygen fuel cell system for future manned spacecraft. The evaluation of base line design concepts and the development of product improvements in the areas of life, power, specific weight and volume, versatility of operation, field maintenance and thermal control were to be evaluated from the material and component level through the fabrication and test of an engineering model of the fuel cell system. The program was accomplished during the period July 1970 - August 1971.

1. SUMMARY

The approach for the program, as specified in the Statement of Work, was to pursue three basic tasks with parallel efforts. Task I consisted of defining a base line design utilizing concepts representing low risk and based on significant prior experience. The fabrication and testing of materials and components of the base line configuration was the approach used to identify and resolve engineering problems.

Task II was focused on the identification and evaluation of concepts which would represent a significant extension of base line capability in the areas of life, power, specific weight and volume, versatility of operation, field maintenance capability and thermal control while still avoiding high technical risk approaches. Those concepts which offered significant improvements were evaluated at the component or subsystem level and introduced as a modification to the base line design where the time phasing with Task I permitted.

Task III consisted of liaison and coordination with the Space Shuttle Phase B Prime Contractors to provide for two-way information exchange in order to perform cost effective system trade-off studies to establish base line fuel cell system requirements.

Management Tasks were implemented for the program planning, resources control, schedule control, NASA liaison and coordination, configuration management and documentation.

Complementary Engineering Tasks, as defined in supporting exhibits to the Statement of Work, were implemented in the areas of Reliability, Quality Assurance, System Safety and Mass Properties Control for the identification and study of factors pertinent to these disciplines which would affect the evaluation of the base line design.

1.1 Task I - Engineering Model

The cell and stack design was a direct outgrowth of work by GE that was sponsored by the Air Force Aero Propulsion Laboratory (Contract F33615-67-C-1830). Modifications were initially introduced to extend life, to produce more uniform cell-to-cell performance and to reduce manufacturing costs. As the program progressed, additional modifications were incorporated to decrease weight and volume, to protect against external reactant mixing and to minimize stress on the solid polymer electrolyte.

The fuel cell container design was a direct extension of the Gemini and Biosatellite spacecraft fuel cell container designs. The basic Gemini container was lengthened to accommodate the larger Space Shuttle size stacks.



Electronic circuits were designed for the control of the fuel cell module. Extensive analysis of ancillary component requirements was completed. Specifications were generated for each of the components. In most cases, ancillary component vendors were selected with experience in aerospace equipment, having produced similar qualified equipment.

The ancillary components related to the fuel cell module coolant loop, hydrogen loop, and oxygen and product water loop were assembled as operational subsystems and operated under simulated mission conditions for 2500, 2000 and 2000 hours, respectively. Only two minor anomalies were encountered.

The coolant pump inverter and major portions of the electrical control system were endurance tested as part of the ancillary component subsystem endurance tests. No problems were encountered with this equipment in any of the subsystem tests.

The voltage regulator design was breadboarded and checkout tested. Voltage regulation was well within specification requirements.

The original small stack test plan envisioned a series of three 8-cell stacks which would confirm the proposed 5 KW Engineering Model EM-1 design. Although many design considerations were adequately demonstrated, cell performance and life limitations resulted in design changes and consequently an additional buildup. In support of this effort, General Electric funded the fabrication and test of one buildup and contributed the use of an advanced ground-application fuel cell stack. In addition to the stack testing, extensive laboratory testing was performed. The net result of the stack and laboratory tests was the identification of the means of extending fuel cell life, identification of the probable cause of low performance, and demonstration that the life limiting condition is not random (i.e., all failures were reactant inlet oriented). The life limiting condition of the fuel cell was the physical/chemical degradation of the solid polymer electrolyte at the reactant inlets. The characteristics of the physical/chemical degradation were increased quantities of hydrogen fluoride carried out with the product water, solid polymer electrolyte delamination at the reactant inlets, and eventual polymer cracking in the delaminated zone. Conditions which were found to prevent or greatly reduce the degradation were the humidification of hydrogen at the reactant inlets and/or removing the cathode catalyst from the inlet area. Corrective actions for increased life will be evaluated under NASA Contract NAS 9-11876.

Engineering Model EM-1 was not assembled as originally planned. The additional unplanned efforts concerning the small stack analyses consumed the available man-hours to the point where it was not possible to complete the fabrication and test of the Engineering Model. However, all of the ancillary components, the containers and much of the cell assembly stack hardware for the Engineering Model were completed.

Task II - Technology Advancement and Exploitation

The second major task concerned the advancement of the state-of-the-art in fuel cell related technologies. The technologies investigated were: variations in the solid polymer electrolyte; materials compatibility; and reactant prehumidification.

Experiments with "R" solid polymer electrolytes were performed. Variations in ion exchange capacities and water contents were fully investigated. The test results indicated that increased fuel cell life could be obtained by increasing the water content (within limits) of the 1200 equivalent weight SPE utilized on this and earlier contracts.

Under the materials compatibility task, three areas were covered: titanium-palladium compatibility; bonding compatibility; and product water system suitability.

The Ti-Pd material was investigated as a possible replacement of the niobium coolant cartridge plates to reduce the weight of the cell assemblies. Because of the difficulty in preventing hydrogen embrittlement and NASA's reluctance to approve the use of titanium in spacecraft, continuing efforts in this area were discontinued.

Evaluations of the bonding systems with and without primer at elevated temperatures in various liquid media were conducted. These evaluations confirmed the potential of long-term fuel cell operation at up to 200°F with distilled water coolant.

An industry search for potential product water separator and wicking materials was made. Samples were obtained of the most promising materials. Test results, however, showed the present porous glass separator and dacron wicking to be superior to any of the evaluated alternates.

Porous glass life tests in hot fuel cell product water were conducted to determine tolerance to hydrogen fluoride. Results showed insignificant degradation of the material at peak operational temperatures for 2000 hours with concentrations up to 10 ppm HF. Significant deterioration occurred at the 50 ppm level.

Part-way through the program, the desirability of prehumidification of reactants was uncovered. As part of the technology advancement task, flight-type humidification concepts were considered. Promising results were obtained on a device utilizing a solid polymer electrolyte without catalyst to transfer moisture from the product water system to the incoming reactants while maintaining a gas seal.



1.3 Task III - Phase B Contracts Activities

A two-way information exchange with prime contractors for system trade-off studies and interface integration was maintained throughout the contract duration. Information provided included:

- . Reactant purity and pressure.
- . Voltage regulation.
- . Voltage level.
- . Module packaging.
- . Program costs vs. life.
- . Module redundancy.
- . Warm-up method.
- . Module sizing vs. peak loads.

1.4 Management and Complementary Engineering Tasks

A NASA-approved program plan (GE document SPR-001) was used as a control and coordination medium. Coordination with NASA throughout the contract was made through the use of monthly reports, quarterly reviews, failure reviews and program reviews.

Supporting activities reports issued included:

- . Reliability Program Plan (GE document SPR-002).
- . Failure Mode and Effect Analysis (GE document SPR-021).
- . System Safety Plan (GE document SPR-009).
- . Hazard Identification and Index Report (Included in GE document SPR-011).
- . Electromagnetic Interference Control Plan (GE document SPR-005).
- . Mass Properties Control Report (Included in GE document SPR-012).

The final reliability report and safety analysis report were eliminated from the program due to the shifting of man-hours to the small stack analysis effort. The EMI testing effort was eliminated for the same reason.

An updated system weight report is included in this report (para. 7.3).

2. CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

1) A base line design was completed for a 5 KW fuel cell module, including detail drawings, component specifications, end item specifications and process control instructions. The module consists of two stacks of 40 cell assemblies each, sized to operate at propulsion tank pressures of 20 to 45 psia and on propulsion-grade reactants. The module is designed with a self-contained Monitoring and Control Unit to completely and safely isolate it from the vehicle in the event of internal failure. The fuel cell module weight is 150 lb or 30 lb/KW.

2) The cell failures encountered during this program can be categorized by the following observations:

- a) All cell failures were in the dry gas inlet areas of the cell.
- b) All cells were delaminated (blistered) at the dry gas inlet area of the cells.
- c) Delaminated areas show oxidative degradation of the polymer, indicating breakage of polymer chains.
- d) Physical properties of the polymer in the delaminated areas have been reduced.
- e) Cell performance is stable and invariant to within minutes of the failure.
- f) The automatic monitoring and control facilities safely isolated the failures in every case.

This experience tends to confirm General Electric's previous findings that random pinholes in the solid polymer electrolyte do not constitute a significant failure mode.

3) An extensive series of failure simulation tests and a matrix of tests to evaluate parameters influencing the degree of delamination and production of HF in product water led to the following conclusions:

- a) Delaminations could not be reproduced outside of operating hardware.
- b) The dominant parameter affecting both delamination and HF production is the degree of humidification of the reactant gases entering the active area of the cell.

- c) A secondary effect noted was that platinized SPE's result in more delamination and HF production than non-platinized SPE's.
- d) Removal of the cathode catalyst in inlet areas eliminates delaminations in that area.

4) The data accumulated plus consultation with various polymer chemists led to the following postulated failure mechanism:

- a) Dry reactant gases entering the cell remove water from the SPE, creating stresses within the polymer as it tends to shrink.
- b) Stress/strain applied to the polymer causes some breakage of the $\leftarrow \text{CF}_2 - \text{CF}_2 \rightarrow$ bonds in the polymer chains.
- c) Hydrogen peroxide produced at the cathode during operation migrates to the weak or broken links in the chain and initiates a free radical attack leaving $\leftarrow \text{CFH}$ and $\text{CFOH} \rightarrow$ which further degrade to HF and CO_2 .
- d) The principle degradation occurs at the center of the SPE, resulting in delamination due either to a concentration of stress at this point caused by the drying and shrinking of one side or by inherent strains or partially broken chains in the center as a result of SPE fabrication.
- e) The weakened and delaminated SPE ultimately develops stress cracks from the continual tensile forces induced by drying of the SPE.

5) In parallel with the fabrication and life testing of the Space Shuttle small stack units, there were two GE-funded test units fabricated into gasketed boilerplate hardware with the same active cell areas and the same SPE and electrode configurations. These were designed as ground power units and differ from space-type units in weight and water removal methods. One of these Advanced Fuel Cell units (AFC 6) was a 4-cell stack which was operated for 3000 hours to the same temperatures (150°F) and load profiles (60, 135 ASF) as the Space Shuttle hardware. Then the operating conditions were increased to 180°F and double the load profile (120, 270 ASF). AFC 6 has operated for an additional 2000 hours at these conditions and is still on test. Released hydrogen fluoride quantities were at the level of detection (≈ 1 ppm). However, AFC 6 had not been exposed to the Space Shuttle multiple stop/start conditions. The other test unit of the same boilerplate construction is a single cell unit (AFC 1) which was on a standby test at a trickle load of 1 ASF for more than 9000 hours at 150°F.

The SPE and electrode configuration of the AFC hardware is the same as configurations used in the Space Shuttle buildups. The key difference is in the conditioning of the reactants in the AFC hardware before reaching the active area of the cells. In the AFC hardware the oxygen is humidified by bubbling through a head of water maintained in the cathode compartment. The hydrogen is introduced at a point below the water level on the opposite side of the SPE. The water head re-supplies water to the SPE in the area where water is being removed to saturate the incoming hydrogen.

6) Major accomplishments in this program were the identification of the life limiting problem encountered in the Space Shuttle hardware configuration and the demonstration of a long life capability for the SPE and electrode assembly of the Space Shuttle size of cell tested in the boilerplate gasketed hardware. The ability to operate the SPE fuel cell on propulsion-grade reactants and at propulsion tank pressures was demonstrated. All of the small stack buildup testing was done without hydrogen purging during the mission operation and the periodic oxygen purging was accomplished with 1% of reactant consumption.

The average single cell performance demonstrated in the small stack buildups is approximately 30 millivolts lower than predicted performance. Investigation as to the cause for this parallel downward shift of the polarization has indicated a contamination of the cathode electrode from constituents of the bonding adhesive material. The loss was consistent between units and stable throughout the life tests. Solutions to this problem were deferred to later follow-on phases of the technology development.

2.2 Recommendations

As a result of the technology evaluation and developments achieved under this contract it is recommended that the following additional efforts be undertaken to further the development of the solid polymer electrolyte type fuel cell for application to the Space Shuttle program and other future manned space flights:

- 1) Fabricate two additional small stack units (4 cell assemblies) and life test for 2000 hours.
 - a) One of the units should be operated with both reactants pre-humidified to saturation in the test facilities to provide a base line evaluation.
 - b) The second unit should include a concept for internally recycling product water to the SPE opposite the hydrogen inlet area as a method of humidification for the incoming hydrogen. The oxygen should be prehumidified in the test facility.

- c) One of the two units should include thermocouples internal to the cell assemblies to obtain thermal data to compare end cell and middle cell conditions, ΔT 's across the cells from coolant inlet to outlet and temperatures at the reactant inlets.
 - d) One of the two units should have individual product water separation systems for the four cell assemblies to evaluate the distribution of HF production and possible correlations with cell performance or cell temperature.
- 2) Continue the matrix evaluations of configuration parameters affecting the HF production, delamination of the polymer and life of the SPE fuel cells.
 - 3) Continue the laboratory evaluation of potential process changes to alleviate conditions shown to be contributing to the limitation of fuel cell operating life.
 - 4) Pursue a program to identify the constituent in the bonding adhesive contributing to the observed performance loss and evaluate changes in formulation to the adhesive or alternate adhesives to eliminate the contaminant.
 - 5) Evaluate the capabilities of cell and ancillary components to operate for satisfactory life at coolant temperatures of 180°F.
 - 6) Fabricate and life test a full stack of cell assemblies (40 cell assemblies).
 - 7) Develop and life test reactant prehumidifiers of flight-weight prototype configurations sized to support operation of a full stack.
 - 8) Evaluate on the small stack unit (4 cell assemblies) the effects of activation methods, cyclic stop/start operations and higher current density operation.
 - 9) Fabricate and life test a complete 5 KW fuel cell module (upon completion of Item 6).

3. TASK I - ENGINEERING MODEL

3.1 Basic SPE Fuel Cell

The primary element of this design is the solid polymer electrolyte. This is a perfluorinated sulfonic acid membrane developed and manufactured by duPont. It provides the functions of electrolyte and hydrogen/oxygen separator. Since the electrolyte is fixed and solid, the electrodes do not have to be designed to retain the electrolyte and therefore can be optimized solely for electrochemical performance and weight. Electrodes consist of platinum black catalyst and an expanded gold electron conducting screen. Figure 1 is a schematic illustrating cell construction and operation.

The basic cell design consists of the SPE electrolyte and electrode assemblies bonded to opposite sides of a coolant cartridge with a hydrogen cavity formed between them. The two niobium plates which make up the coolant cartridge are separated electrically to permit the SPE and electrode assemblies to be electrically in series, placing a different electrical potential on each of the two plates. Cooling the cell is accomplished by circulating water through the coolant cartridge.

A bus bar along two opposite edges of each electrode is used to conduct electricity to series and paralleling tabs external to the cell. A coolant cartridge sandwiched between the two SPE and electrode assemblies cools the cell and provides the channel for hydrogen distribution over the face of the anodes.

The oxygen side consists of a labyrinth distribution screen and a wick sheet which removes the product water from the electrolyte. Integral manifolds with built-in restrictors are used for the coolant, hydrogen and oxygen.

The product water accumulates on the wetproofed cathode (oxygen electrode) and is transported by capillary forces through the wick and then into a water removal system via a porous water separator. The separator permits water to flow under a pressure differential but forms an effective gas seal.

Figure 2 shows the basic cell stack assembly. The stack assembly employs a gasketed labyrinth screen assembly adjacent to each module face. This screen assembly, when compressed within the stack, provides integral manifolding for O₂, H₂ and coolant, O₂ distribution within each cell, and a path for product water removal.

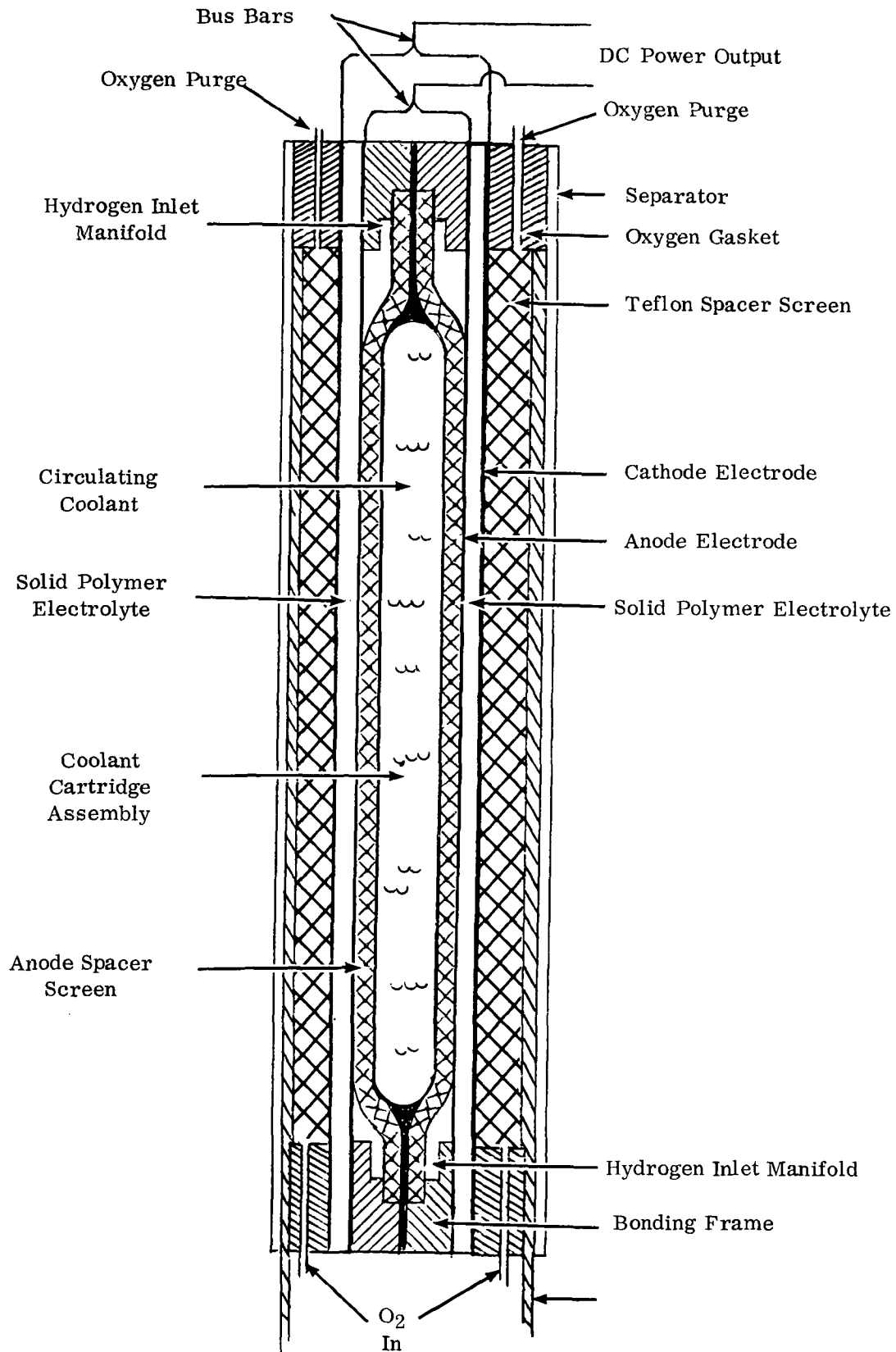
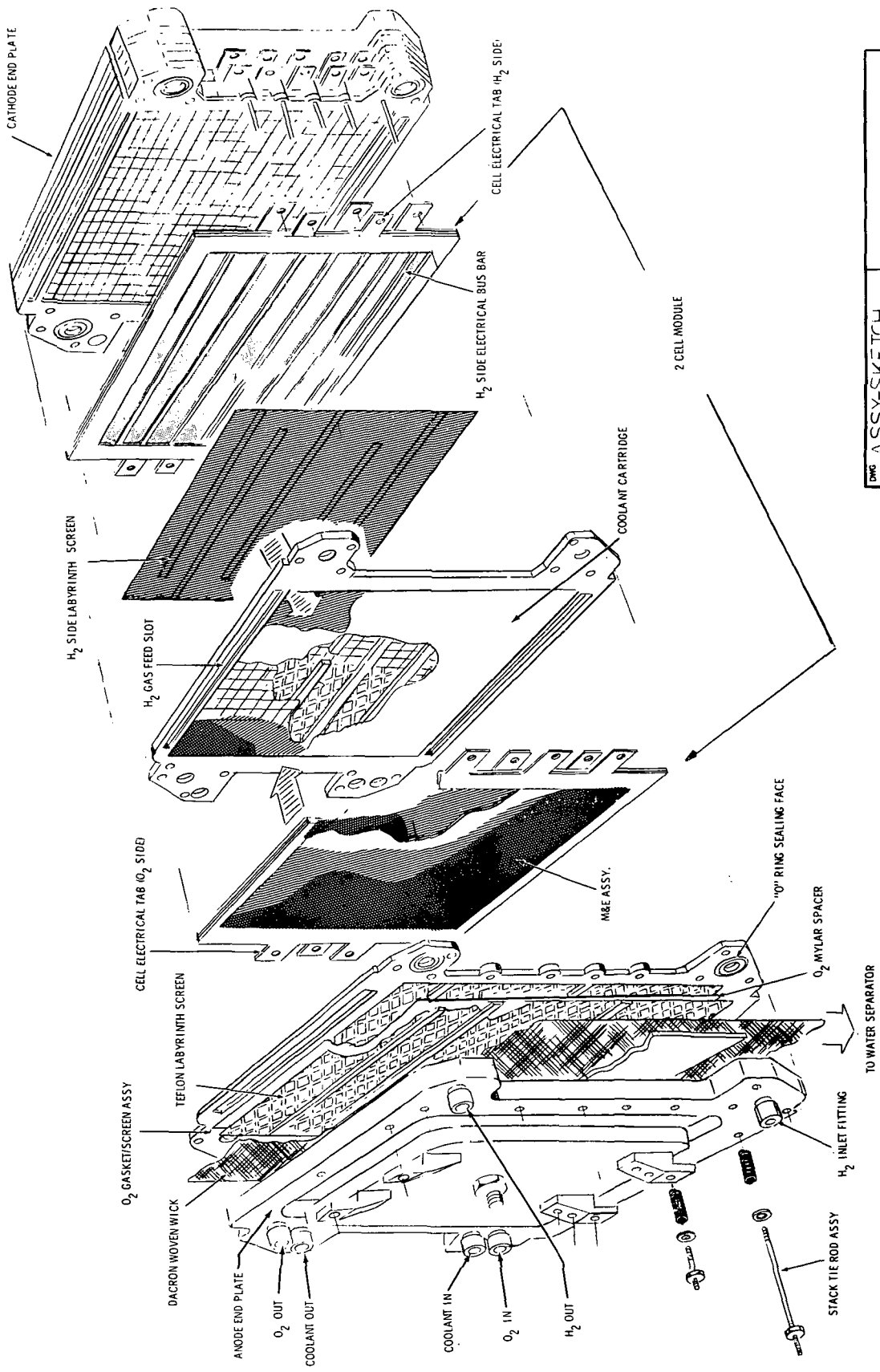


Figure 1. Back-to-Back Fuel Cell Assembly Schematic



DWG TYPE		ASSY-SKETCH		A	
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES		SIGNATURES		MO. DA. YR.	
✓		DRAWN BY		4/17/72	
ALL SURFACES		CHECKED		4/17/72	
MATERIAL		DATE		4/17/72	
FOR G.E. USE ONLY		SIZE		CODE IDENT NO	
SIMILAR TO		D 14736		1075527-720	
L/O		SCALE		WT. SCALE	
FOR		SHEET		SHEET	

Figure 2.

3.2 Cell and Stack Design

3.2.1 Initial Design

At the start of the fuel cell technology program, a cell and stack design was generated utilizing the experience and recent developments in other fuel cell and electrolysis programs. As test data was accumulated and analyses completed, modifications were incorporated. The initial Space Shuttle cell and stack design utilized the newly developed extruded solid polymer electrolyte. This recent duPont process development resulted in a 30 to 50% increase in polymer strength. Other features included in the design were:

- a) A General Electric developed stabilizer was added to the solid polymer electrolyte to minimize hydrogen peroxide attack of the polymer.
- b) Davon-24 bond primer was included in all the bonded joints except the membrane bond. This primer increased significantly the aged bond strengths of the various components.
- c) The hydrogen purge system was eliminated from the design since inert removal by diffusion to the oxygen cavity was demonstrated on Advanced Fuel Cell units. This provided for a simpler overall fuel cell system.
- d) A porous Teflon wetproofing was introduced on the cathode assemblies. This provides a more uniform electrical performance by reducing variations in diffusion rates.
- e) One-edge wicked water removal was incorporated to give the oxygen gas cavity a three-sided gas seal thus allowing reduced purging volumes to remove inerts.
- f) Low catalyst loadings and simple current collection assemblies provided for relatively low cost electrode assemblies.

Further analysis resulted in the first series of cell and stack design modifications. For the most part, these modifications were generated for the purpose of simplifying assembly and minimizing weight and volume. These changes included:

- a) Lightweight end plates with titanium frame and honeycomb center plate. This design provides cell-to-cell electrical contact forces as well as manifolded sealing forces.



- b) All fluid ports on one end plate. This enables minimum volume installation of two stacks within the EM-1 container.
- c) Simplified cell-to-cell electrical connections, incorporating longer bus bar tabs to allow direct cell-to-cell tab contact.
- d) Alternate cell assemblies have bus bar tabs of opposite potential.
- e) Redesigned O₂ frame assembly to include attached rubber compression springs to provide cell-to-cell electrical tab contact forces. Also added O₂ sealing beads to insure three-side gas seal.
- f) Tabs added to O₂ spacer to support electrical compression springs.
- g) Lightweight and smaller product water removal system with single necked-down wick for each SPE and electrode assembly.

3.2.2 Further Design Modifications

Endurance testing on early Space Shuttle buildups revealed life-limiting design deficiencies. A second series of design modifications were thus incorporated. These included the following:

- a) Compartmentalization of the H₂ cavity to reduce the amount of dry inlet gas that passes over any given point on the cell was accomplished by making the following changes:
 - . Addition of a polysulfone grid pattern molded into the H₂ distribution screen.
 - . Add a second H₂ inlet channel and manifold at the top edge of cell assembly.
 - . Add grid pattern to coolant cartridge plates to match pattern in H₂ distribution screen.

This revised configuration was designed to divide the H₂ compartment into eight 3.7 x 1.9 inch areas to duplicate the H₂ inlet conditions present in the 3 x 3 inch laboratory units. From the patterns of failures and delaminated SPE's in early buildups it was concluded that all the H₂ was flowing over the bottom third of the cell. Since the active area of the 3 x 3 inch cell is .05 ft² compared with .375 ft² in the Space Shuttle cell, the H₂ flow velocity at the H₂ inlet of the Space Shuttle cell was approximately .375/.05 or 7.5 times that in the laboratory unit at any given current density.

In the revised design, flow of H₂ between the small compartments is minimized by the molded polysulfone ribs in the hydrogen screen assembly. Hydrogen flows into each small compartment from the top or bottom H₂ channel. Thus, the H₂ flow velocity over any given point on the anode is considerably reduced (see Figures 3 and 4).

b) A catalytic scavenger was introduced into the H₂ inlet channels to prevent failure from small amounts of oxidant mixing with the fuel upstream of the cell.

c) Higher water content SPE (36 to 40 wt %) was incorporated into the SPE and electrode assemblies by an autoclaving process to improve the internal water diffusion rates.

d) Figure 5 shows modifications to the SPE and electrode assembly and bonded joint that were introduced to separate the SPE bond stress condition from H₂ inlet stress area. The width of the collector strips was increased from .060 to .125 inch so that the electrode screens could be terminated at the centerline of the collector strips. This effectively prevents the screen strands from overhanging the collector strips and puncturing the SPE during the bonding cycle.

e) The suspected high stress point at the inner edge of the SPE and electrode to the SPE and electrode frame bond was considered to be too close to the H₂ inlet area, also subject to drying stresses. Consequently, the collector strip and inner edge of the AF-42 bond film was moved outward to reduce the additive stress condition.

f) The anode catalyst loading, which has been reduced to 4 mg/cm² for cost reduction was increased to 30 mg/cm² to provide a larger mass transport barrier to local drying of the SPE at hydrogen inlet areas.

In order to increase saturation of the oxygen entering the O₂ system compartment, the inlet configuration was modified as follows:

- 1) Increased length of O₂ inlet tubes so that gas would be introduced at a point of greater water content in the product water wick.
- 2) Placed the O₂ inlet tube behind the product water wick.
- 3) Added a second layer of wicking in the O₂ inlet region.

The configuration of the stack assembly was modified as follows:

- 1) Addition of a second H₂ inlet port for the top H₂ channel.



- 2) Relocation of the water separator to the bottom of the stack to assure more uniform wick water content and prevent back-flow of separator contaminants to the SPE. (Zero "G" water removal capability was demonstrated in B/U 1 and 2.)

The life-limiting deficiencies were found to be more subtle than envisioned during the first series of corrective action design modifications. Although the precise mechanism of SPE delamination and failure was not identified, laboratory tests demonstrated two methods of minimizing the conditions. Maintaining SPE moisture at reactant inlets and/or eliminating the cathode catalyst from the inlets were the features that greatly reduced the degradation. The introduction of these new features into the cell and stack design (Figure 6) and the endurance test evaluation will be covered in NASA Contract NAS 9-11876 final report. The effort under that contract is intended to demonstrate improved cell life in two small stack buildups and to continue laboratory fuel cell tests to identify potential improved configurations.

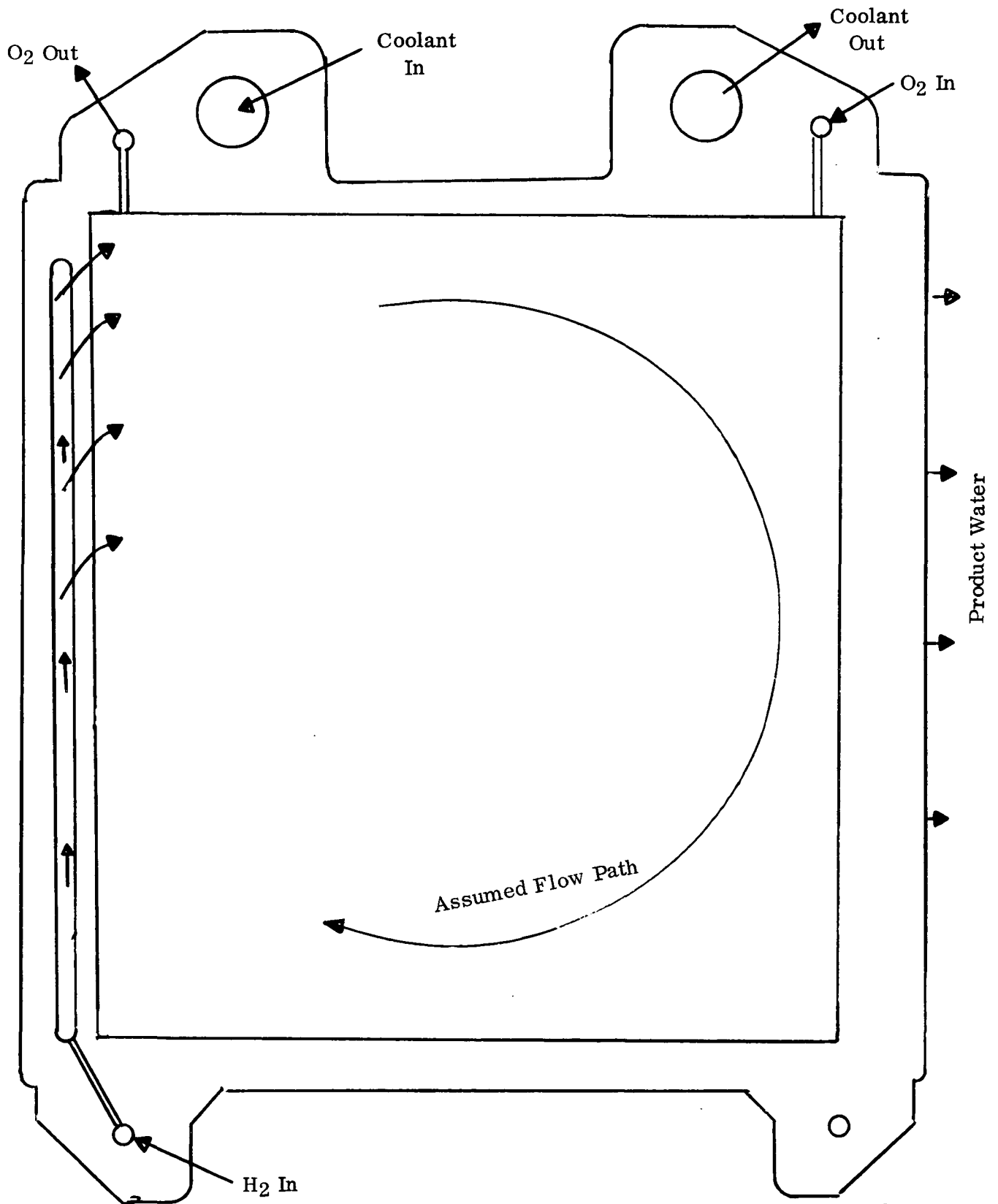


Figure 3. Hydrogen-Side Cell Configuration for Buildups 1, 2 and 3

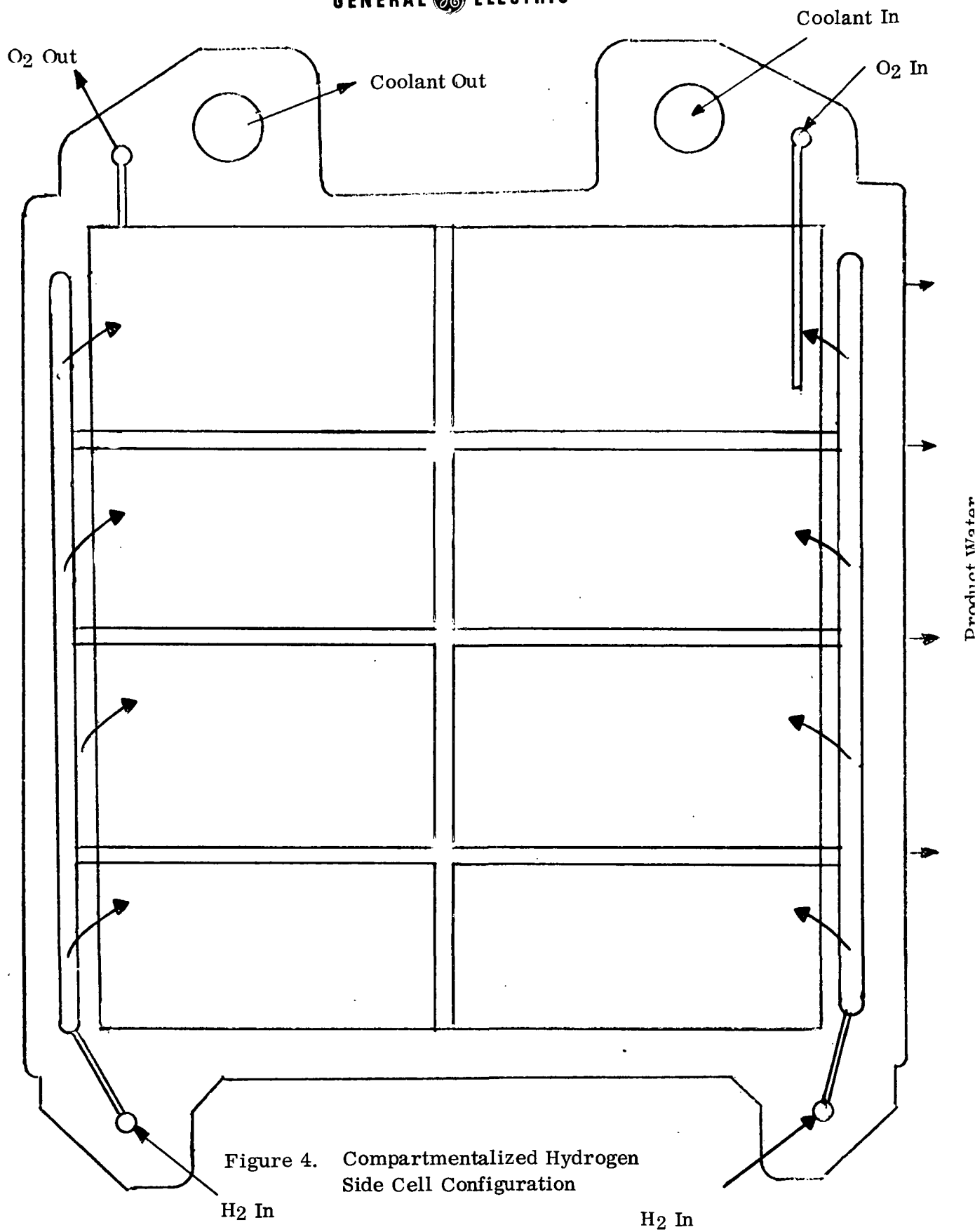
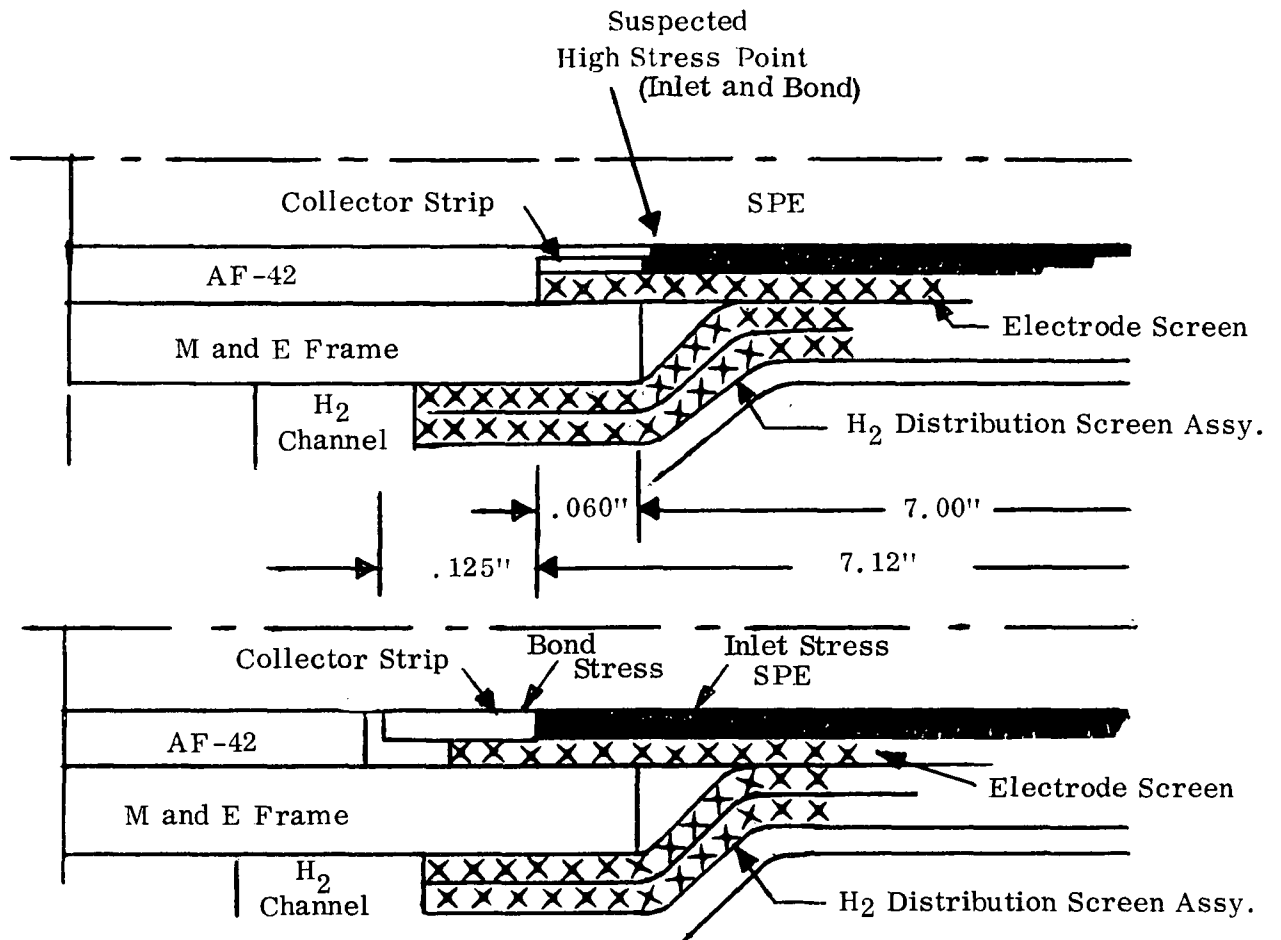


Figure 4. Compartmentalized Hydrogen Side Cell Configuration



- Note:
- 1) Collector strip width increased from .060" to .125".
 - 2) Active area width increased from 7.00" to 7.12".
 - 3) Electrode screen edge centered on collector strip to prevent puncture of SPE by loose strands.
 - 4) Edge of SPE bond no longer in line with edge of M and E frame.

Figure 5. Modifications to SPE and Electrode Assembly and Bonded Joint

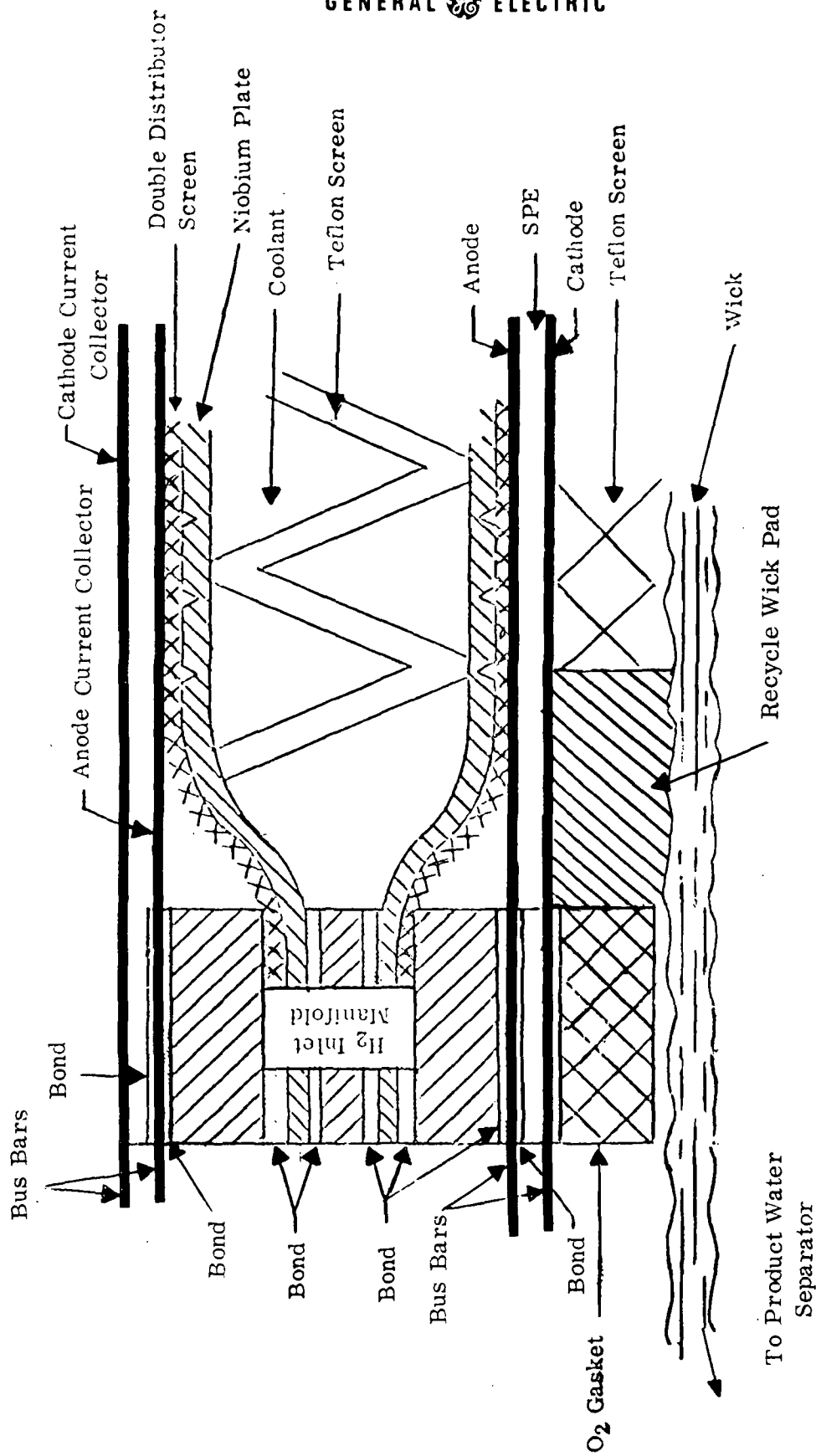


Figure 6. Cross-Section of Back-to-Back Cell Assembly

3.3

Fuel Cell Module Design

The base line 5 KW rated fuel cell module consists of two stacks of 40 cell assemblies each. The cell assemblies consist of two cells with 0.35 ft² of active area per cell bonded to a single cooling cartridge. The two cells are connected in parallel resulting in an active area of 0.70 ft² per cell assembly. Figure 7 shows the performance capability of the single cells and the two-stack module operating at 150°F.

The solid polymer electrolyte fuel cell has the capability to operate at any temperature from 40 to 200°F without the need for any external heating. This allows a great deal of flexibility to design trade-off studies for optimizing operational parameters. The average single cell performance vs. temperature is shown in Figure 8. The fuel cell module performance vs. temperature is shown in Figure 9.

The base line fuel cell module design also provides for a great deal of flexibility in the selection of optimum output voltage levels. Nominal output voltages of 28, 56 and 112 VDC can be obtained by simply altering the connections between cells in a cell assembly from parallel to series and altering the connections between stacks from parallel to series.

Peak power output vs. minimum voltage levels may also be easily adjusted to optimize the base line design to any particular application requirements by changing the number of cell assemblies per stack and the number of stacks incorporated into a module. An example of this flexibility is shown in Figure 10.

The pneumatic schematic for base line fuel cell module design is shown in Figure 11. The two stacks are packaged into a single container which provides the structural support for the whole module and is filled with the oxygen reactant at operating pressure. Attached to each stack are fritted glass water separator tubes that remove the product water from the cell wicks and separate the water from the gas environment with a ΔP of 3 to 4 psia across the capillaries of the porous glass tubes. The water transport rate is thus completely self-regulating and governed by the amount of water produced in the cells. The water separator is also self-sealing when no water is produced as in the case of open circuit standby of the cells. A regulator on the product water delivery line is referenced to the oxygen pressure to maintain the desired ΔP across the separator.

The reactant supplies are regulated to the desired operating pressure with regulators mounted on the module container. The hydrogen regulator is referenced to the regulated oxygen in order to maintain an O₂ over H₂ ΔP of 4 psia. The oxygen pressure may be set at levels from 20 to 50 psia, or may be permitted to drift from 50 down to 20 psia allowing the flexibility to optimize the system with storage tank pressures. The oxygen pressure is maintained above the hydrogen pressure as a safety device in the event of cell failure, such that any mixing of the reactants will occur within the very small volumes of the hydrogen compartment and adjacent to the



cooling cartridge. Check valves in the hydrogen line to each stack prevent the spread of oxygen leakage from one stack to the other in the event of failure.

Each stack has solenoid-activated purge valves for both hydrogen and oxygen. The hydrogen valves are used only for initial vacuum charging of the system and during in orbit stop/start procedures. The oxygen purge valves are controlled automatically by the Monitoring and Control Unit.

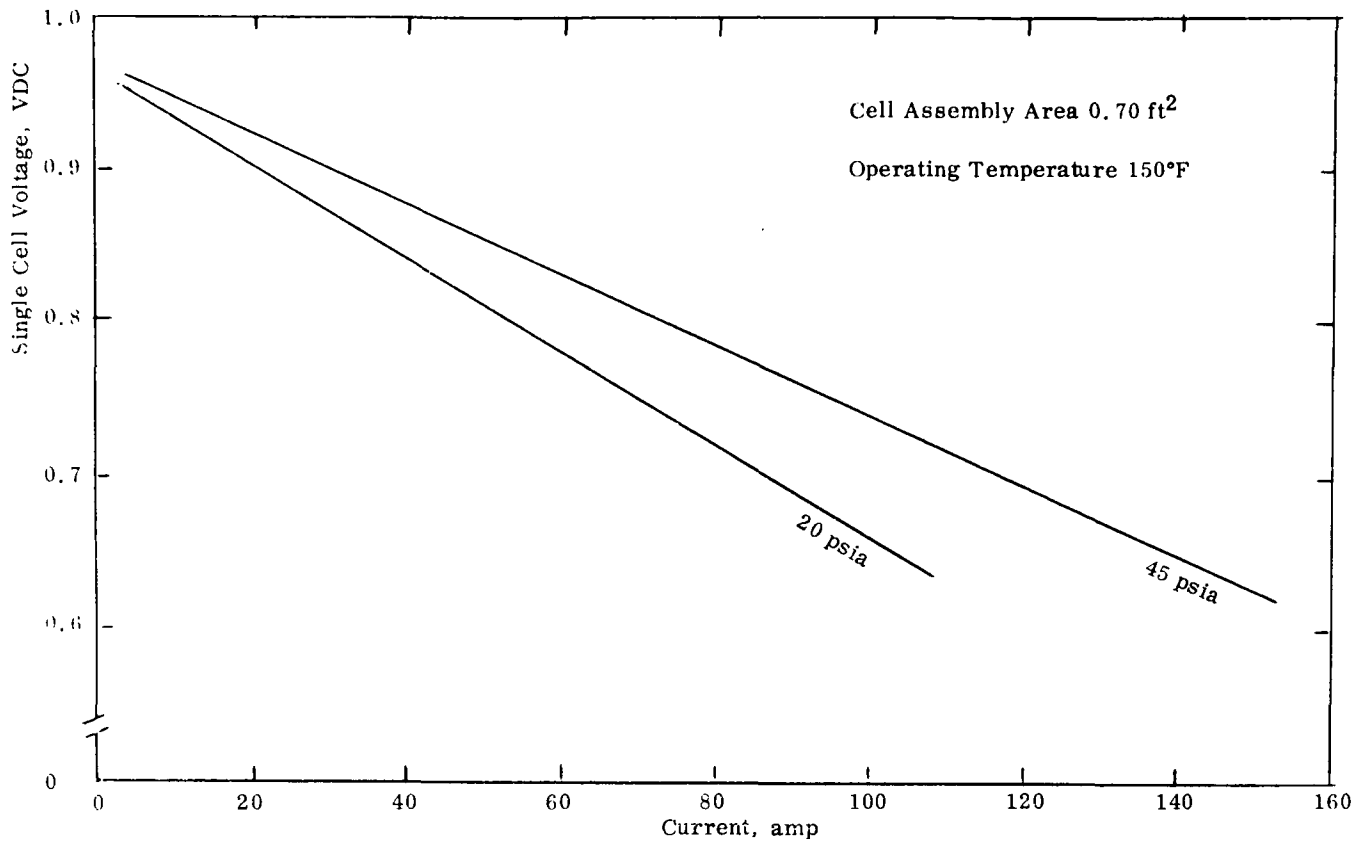
The cooling system consists of a circulating pump and an accumulator which is referenced to the regulated oxygen to circulate coolant through the cell cooling cartridges and the stacks in parallel and at a pressure which is balanced with the oxygen chambers. Restrictive tubes are built into the exits of the cooling cartridges to assure uniform flow distribution between cells. The circulating pump draws 90 watts of power while delivering 4.5 gpm. A thermal control valve in the coolant loop regulates the bypass flow around the heat exchanger to maintain a constant coolant temperature at the inlet to the module. The thermal control valve uses a eutectic wax for the driving power to operate the regulator. Deionized water is used as the cooling fluid in the base line design.

The fuel cell module is also equipped with latching solenoid valves on the high-pressure side of the reactant regulators and on the product water outlet line. These valves are only used to shutdown the module and completely isolate it from the remaining module(s) of the power system.

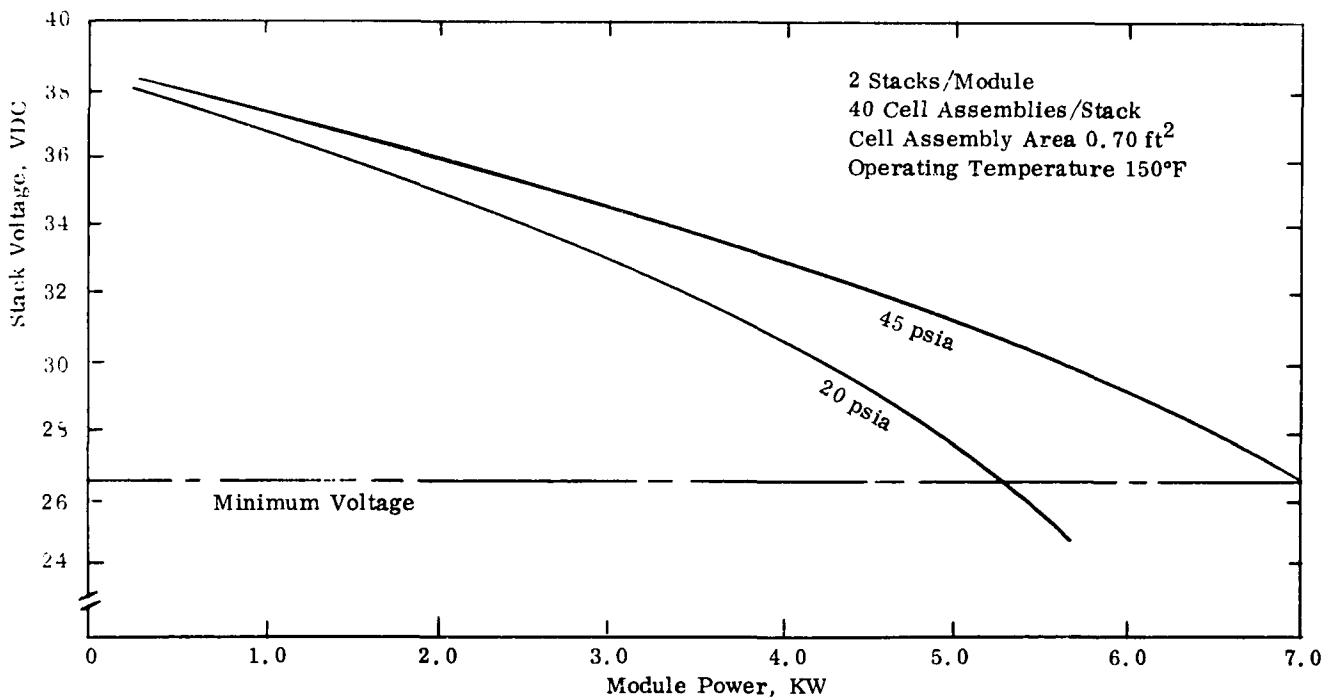
The base line fuel cell module contains an electronic monitoring and control unit not shown on the schematic. The MCU monitors signals from the pressure transducers shown in Figure 11 and also monitors the current difference between the two stacks. In the event that any of the sensors exceed the preset limits to indicate failure, the MCU will automatically activate the latching solenoid valves and the line contactor to remove the module from the line. The MCU also provides the signal conditioning to transmit diagnostic data to either a central computer system on the vehicle or to a pilot display panel.

The base line fuel cell module described above weighs 150 lb dry (30 lb/KW). The cooling system fluid and the charged product water system add approximately 21 lb of water.

The overall dimensions and a typical mounting arrangement for the ancillary components of the 5 KW fuel cell module are shown in Figure 12.



Single Fuel Cell Performance



Two-Stack Fuel Cell Module Performance

Figure 7

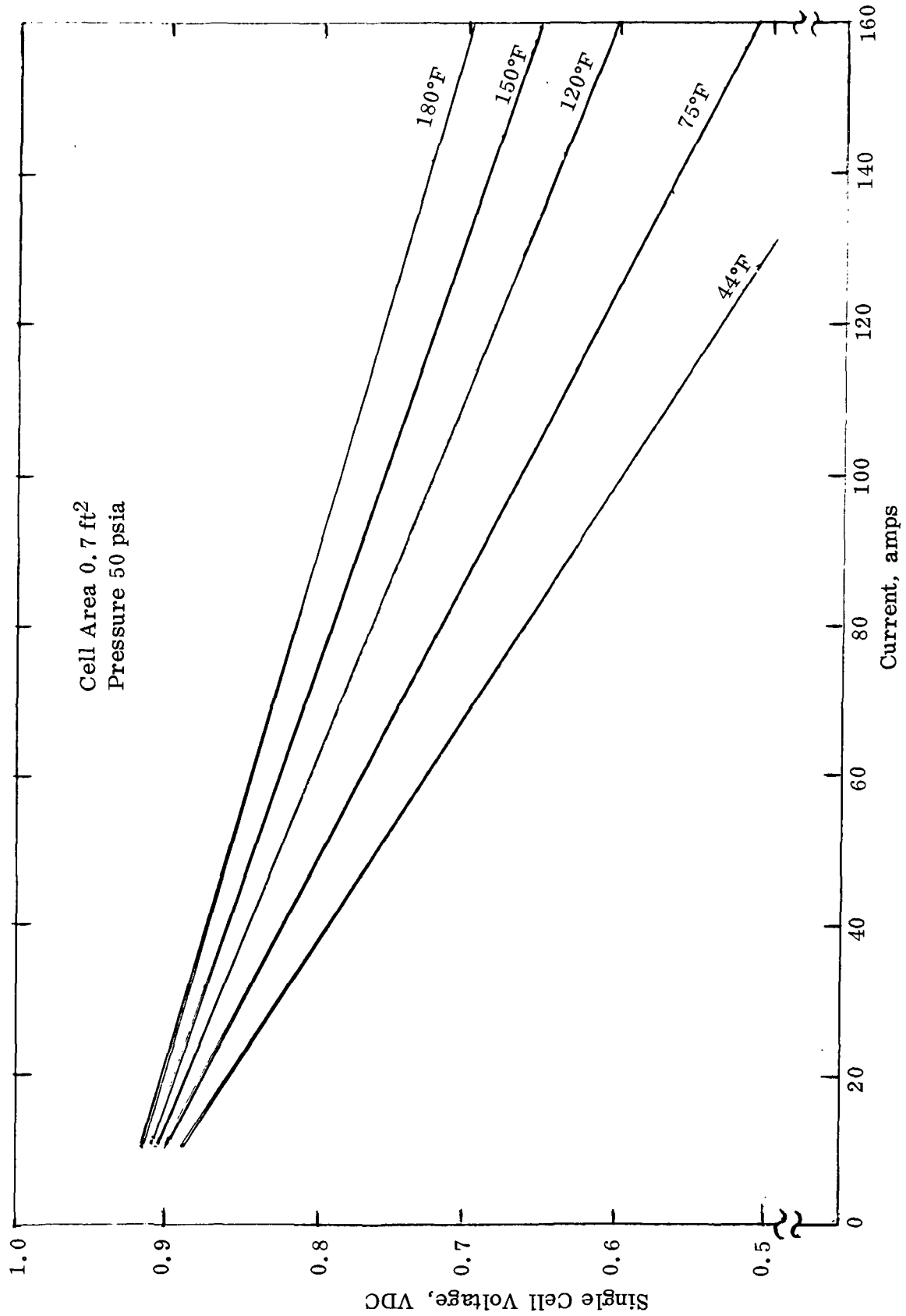


Figure 8. Single Fuel Cell Performance vs. Temperature

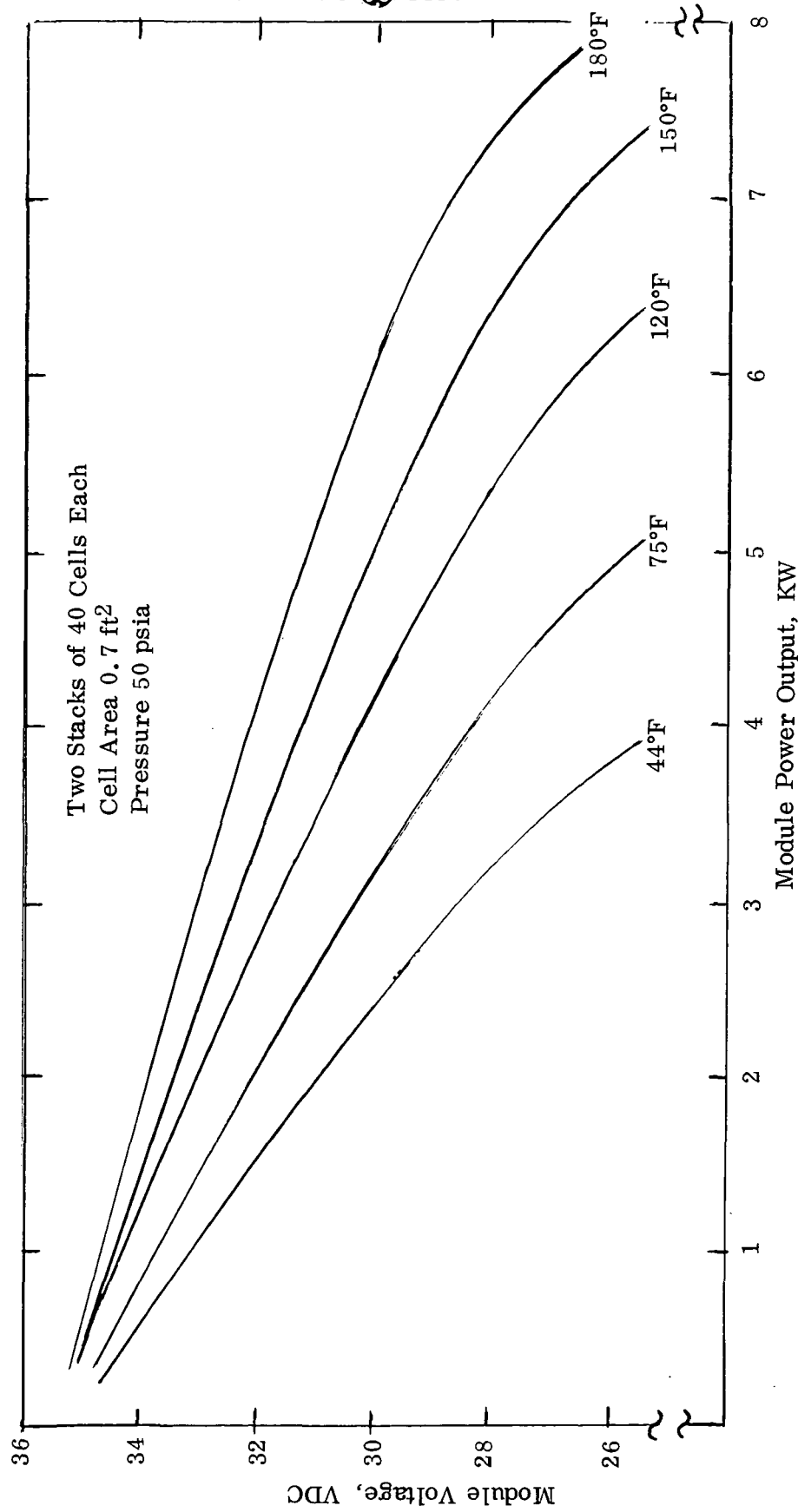


Figure 9. Fuel Cell Module Performance vs. Temperature

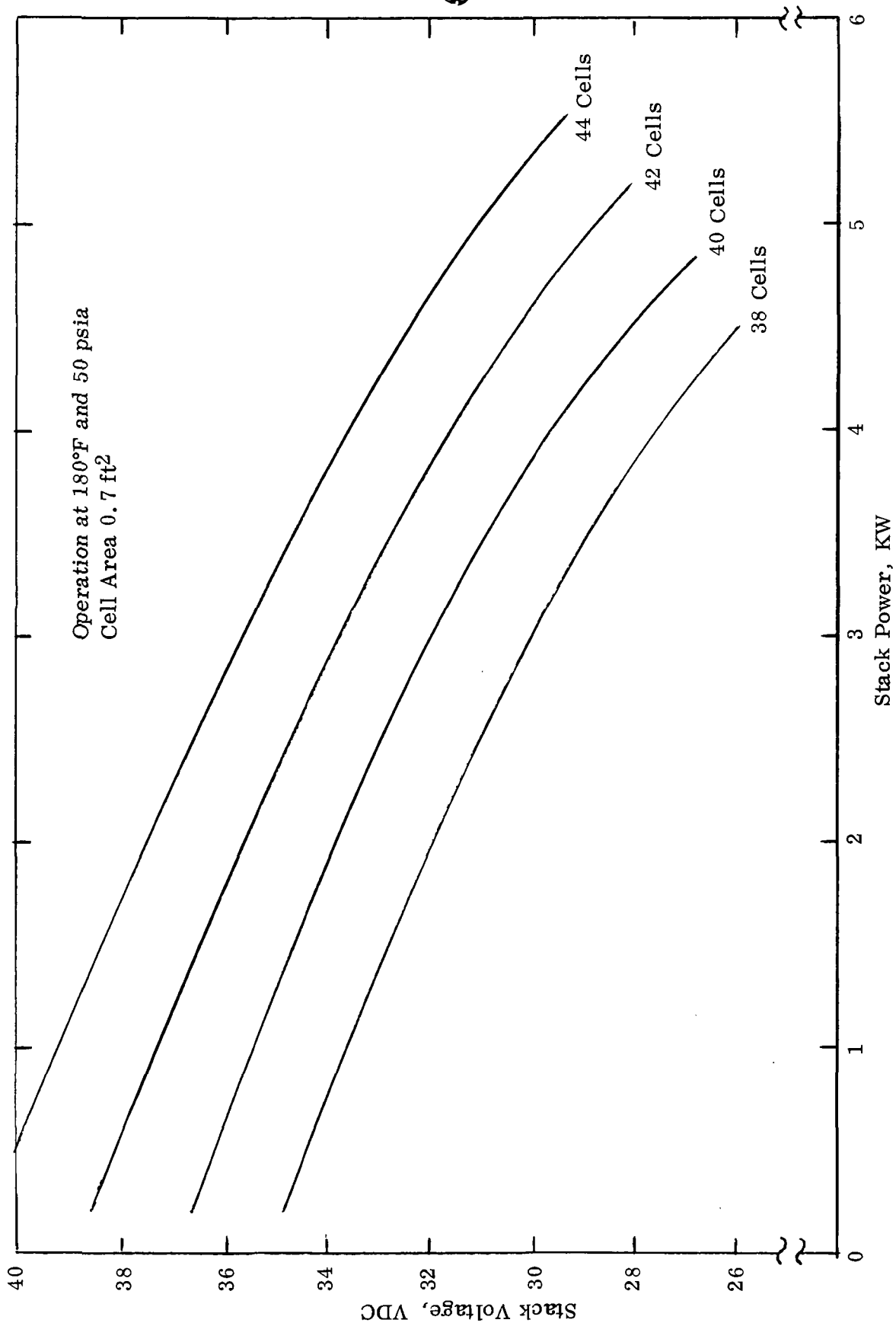


Figure 10. Fuel Cell Stack Performance vs. Number of Cells

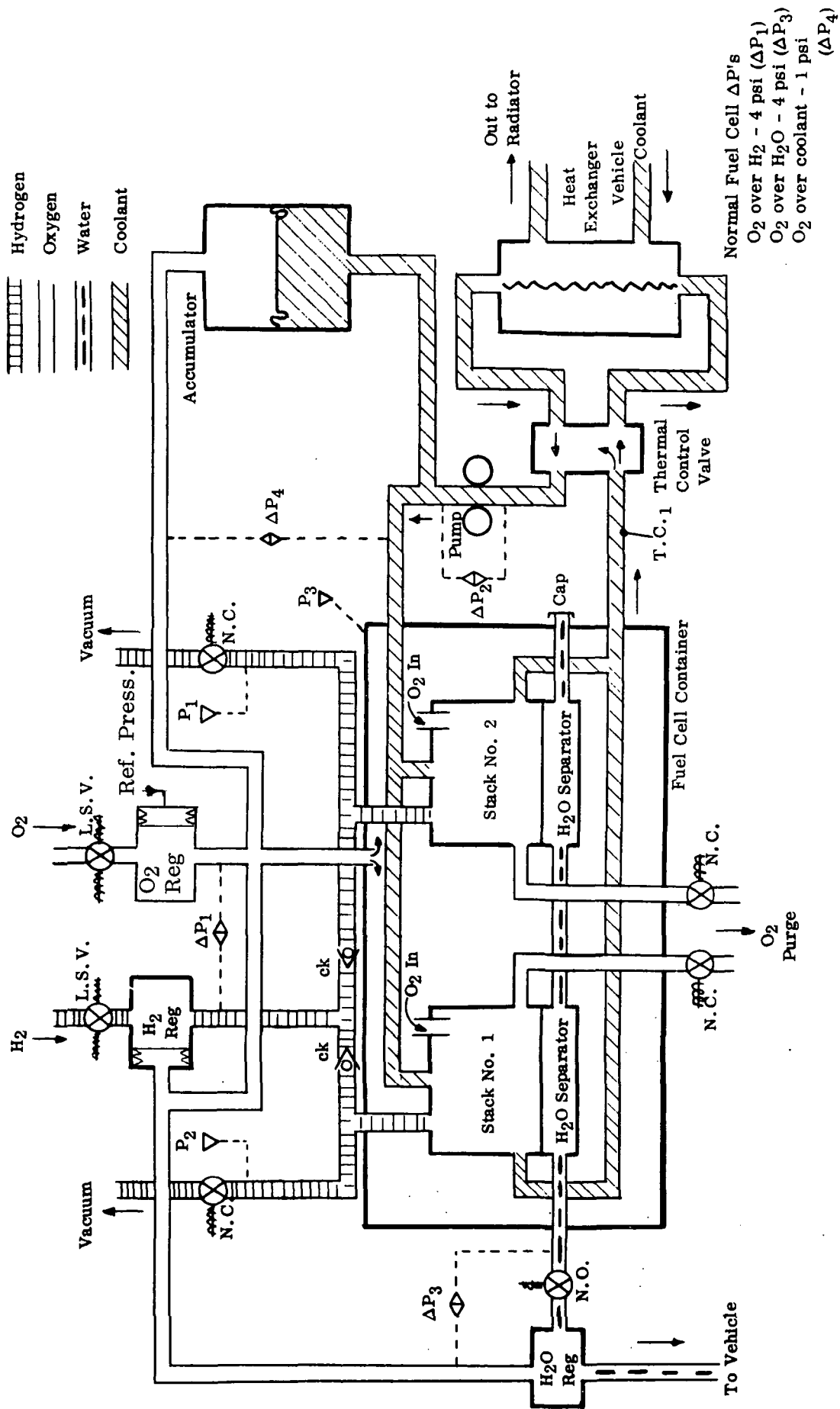


Figure 11. Fuel Cell Module Pneumatic Schematic

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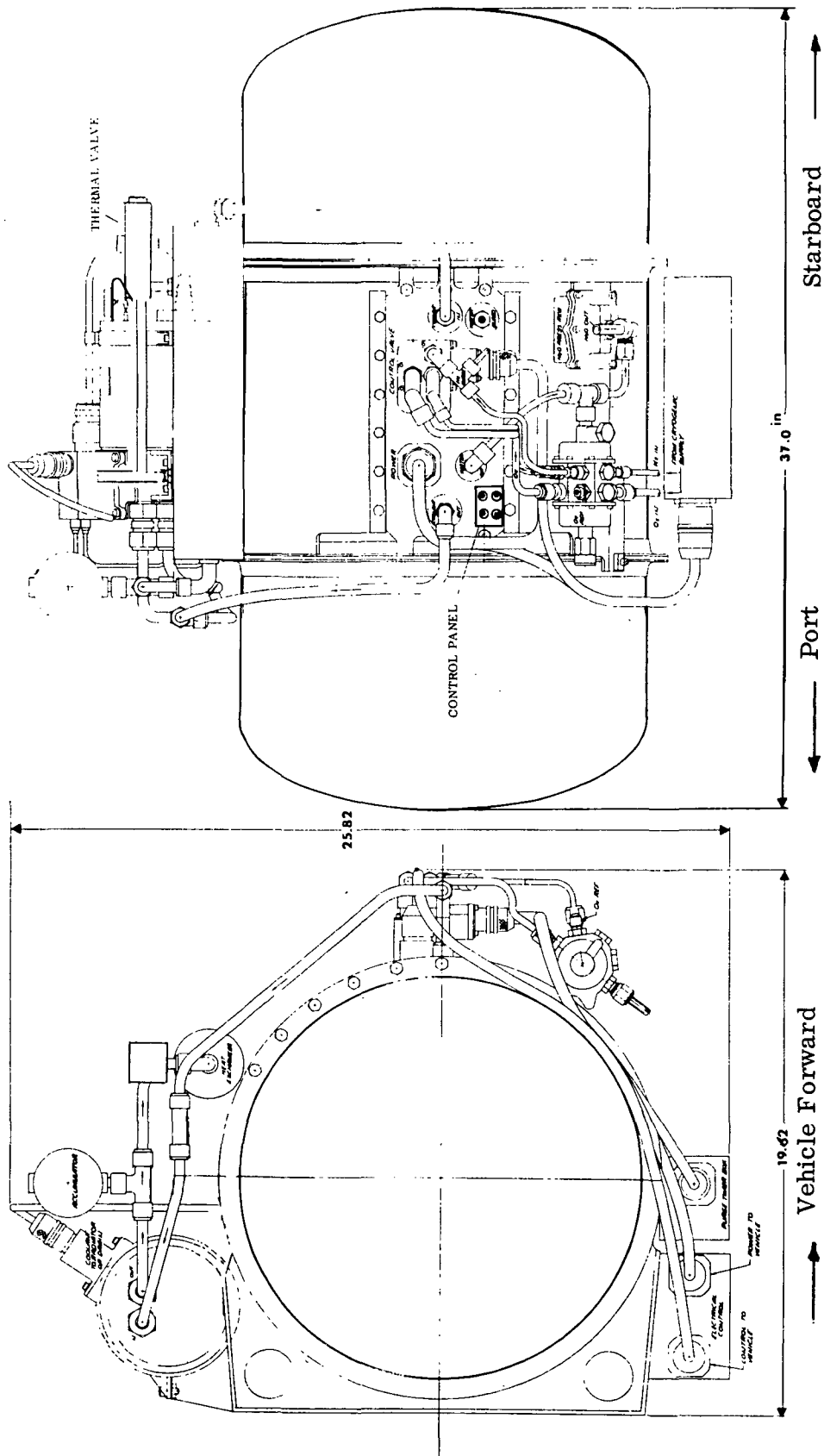


Figure 12. Fuel Cell Module and Ancillary Components Mounting Arrangement

3.4 Container Design

The Gemini/Biosatellite fuel cell container design was used as the building block for the Space Shuttle design. This basic design has been space qualified, safety-explosion tested, and flown in space without anomalies. The end domes were modified for the additional length of the Space Shuttle stacks and for the somewhat higher maximum operational pressure. This design utilized titanium as the primary construction material. Due to recent concern over the use of titanium in the presence of oxygen, an alternate material(s) should be investigated.

3.5 Electronic Controls

The electronic control subsystem was designed to the following requirements. Circuit design drawings for the electronic controls are shown on drawings 1076527-802 thru -807 and -835 which are included in the Appendix.

3.5.1 Voltage Regulator Requirements for EM-1

The following characteristics and functions shall apply to the voltage regulator:

- 1) Unregulated DC power (45 to 28.1 volts and 0 to 215 amps) shall be regulated to 26.6 to 29.4 volts DC.
- 2) Maximum voltage loss at 215 amps to be 1.5 volts.
- 3) Connectors and cables to connect with Monitoring Control Unit to carry 215 amps.

3.5.2 Monitoring Control Unit (MCU) Requirements for EM-1

The MCU shall be fabricated in a breadboard form. The following characteristics and functions shall apply to the MCU:

- 1) Each fuel cell stack will be wired to its own Amphenol connector located on the accessory pad. The two Amphenols will be Model No. 48-13H-22-12P-116. The pin connections for polarity are to be determined. Wiring with 215 amp capability will connect the stacks to the MCU. A current sensor for each stack will be located between the accessory pad and the voltage regulator contactor.

Within the MCU the electrical main power leads will be attached to a contactor (voltage regulator contactor - VRC). The VRC will direct the main power leads to the voltage regulator location. These leads shall have a 215 amp capability. This VRC will be operated both upon a manual or automatic signal.

- 2) An electrical lead connection shall be made to the power leads between the fuel cell stacks and the VRC. These leads shall terminate in a connector. These leads shall be capable of carrying 50 amps for the purpose of electrical charging or impedance measurement with the VRC open.
- 3) Following the voltage regulator location, the main power leads with the 215 amp capability, will be attached to the main bus contactor (MBC). This MBC shall be both automatically and manually operated. Functions automatically operating the VRC and MBC will be covered separately.
- 4) An inverter shall supply a 3 phase, 300 Hz, DC power up to 100 watts, based on sinusoidal wave function, to the coolant pump.
- 5) The current sensors in the power leads of each stack shall be utilized to determine amperage performance of the stacks.
- 6) An O₂/H₂ ΔP transducer signal at a 1 psid or less shall automatically open the VRC and MBC and close the hydrogen inlet latch valve. The hydrogen inlet latch valve shall be interlocked closed whenever the O₂/H₂ ΔP is +1 psid or less (no manual override).
- 7) An oxygen purge timer shall be included in the MCU. This device shall monitor the total fuel cell module amperage output and shall automatically activate the two oxygen purge valves open in sequence for 5 seconds each with a 10 second delay between purges for each 35 amp-hours of operation. In addition, a manual purge signal capability with automatic purge timer reset shall be provided.
- 8) The hydrogen inlet latch valve shall be interlocked closed by the pressure signals from the hydrogen systems of the two fuel cell stacks. The hydrogen inlet latch valve can only be opened with a low pressure signal from the two stacks.
- 9) An external power supply shall supply $28 \pm 5\%$ volts to the MCU for the purpose of supplying power to the valves, contactors, pump, and signal devices.
- 10) The MCU shall be a junction box supplying power to all fuel cell module condition signals. Signals and functions:
 - a) O₂/H₂ ΔP (1 psid or less) close VRC and MBC and hydrogen inlet valve. Condition light signal to operational control panel.

- b) Low hydrogen pressure in each stack (5 psia or less) break hydrogen inlet valve interlock. Two lights on control panel (one per stack).
 - c) Low coolant pump ΔP (3 psid or less) light on control panel - opening the VRC and MBC following one minute of low ΔP . (The one minute is not firm at this point -- may be anywhere between 1 and 60 seconds.)
 - d) High coolant outlet temperature (180°F) light signal at control panel and automatic opening of the VRC and MBC.
 - e) O₂/coolant ΔP signal (0.0 or less psid) light.
 - f) O₂/H₂O ΔP signal (2 psid or less) light.
 - g) O₂ pressure low (20 psia or less) light.
- 11) Panel controls through MCU shall be as follows:
- a) H₂ inlet latch valve open and close (light indication).
 - b) H₂ vacuum valves (2 each) open - close.
 - c) O₂ inlet latch valve open and close (light indication).
 - d) O₂ purge valves (2 each) open and close.
 - e) Product water valve open and close (light indication).
 - f) Main bus contactor open and close (light indication).
 - g) Voltage regulator contactor open and close (light indication).
- 12) Direct voltage readout from module terminals to control panel shall be supplied.
- 13) A reverse current sensor shall be supplied between MBC and the main bus connector(s) for the purpose of detecting "shorts" within the fuel cell module equipment. The VRC and MBC shall be automatically open and the hydrogen latch inlet valve shall be automatically closed upon a reverse current signal.

3.5.3 Test of Electronic Control Subsystem

Portions of the electronic control system were life tested simultaneously with the ancillary component life tests (see section 3.7). These included:

- . 28 VDC to 28 volt 300 Hz, 3 phase AC inverter for coolant pump motor power. Tested for 2500 hours.
- . Coolant transducer readouts with automatic shutdown with pump ΔP of less than 4 psid vs. 11 psid normal. Tested for 2500 hours.
- . Hydrogen to oxygen transducer readouts, with automatic shutdown with O_2/H_2 ΔP of 1 psid or less vs. normal 4.0 psid. Tested for 2000 hours.

The above electronic devices operated for the entire test program without anomalies.

The breadboard voltage regulator was originally scheduled to be life tested with Engineering Model EM-1. Due to the deletion of fabrication and testing of EM-1, no endurance testing of the breadboard regulator was performed.

Checkout of the regulator was performed utilizing a fork truck battery. Sustained power could not be obtained from this fork truck power supply, thus it was only suitable for checkout and demonstration of the regulator.

The initial checkout testing of the voltage regulator was within specification regulation. However, testing was terminated after failure of a power transistor. The probable cause was analyzed to be a spike overvoltage. Design modifications were incorporated to prevent the overvoltage and successful checkout of the equipment was accomplished. The hardware was placed in bonded storage for future use.

3.6 Ancillary Components

The following is a general description of the major ancillary component functions. Table I lists component quantities per module.

- Part 1 - Absolute pressure transducers. The transducers were installed to monitor the pressures in the oxygen, hydrogen, coolant and product water systems. Various combinations of pressure readouts will result in automatic fuel cell module shutdown while others will give a warning signal only.

Table I
Fuel Cell Module Parts List

<u>No.</u>	<u>Component</u>	<u>Qty/Module</u>
1.	Absolute Pressure Transducer	5
2.	Hydrogen Pressure Switch	2
3.	Latching Solenoid Hydrogen Valve	1
4.	Hydrogen Pressure Regulator	1
5.	Hydrogen Check Valve	2
6.	Evacuation Valve-Hydrogen	2
7.	Evacuation Orifice-Hydrogen	2
8.	Coolant Accumulator	1
9.	Coolant Pump and Motor	1
10.	Thermal Control Valve	1
11.	Coolant Inverter	1
12.	Coolant Heat Exchanger	1
13.	Coolant Overtemperature Switch	1
14.	Latching Solenoid Oxygen Valve	1
15.	Purge Valve-Oxygen	2
16.	Purge Orifice-Oxygen	2
17.	Oxygen Inlet Check Valve	1
18.	Latching Solenoid Valve-Product Water	1
19.	Product Water Pressure Regulator	1
20.	Module Internal Product Water Removal Subsystem	1
21.	Electrical Wiring Harness	1
22.	Module Control Unit	1
23.	Voltage Regulator	1
24.	External Structures	1
25.	Internal Structures	1
26.	Internal Piping	1
27.	External Piping	1
28.	Module Container	1
29.	O ₂ Screen and Frame Assembly	80/stack, 2 stacks/module
30.	Cell Assembly	40/stack, 2 stacks/module

- Part 2 - Hydrogen pressure switches. The hydrogen pressure switch indicates when the stack hydrogen pressure is less than 5 psia and in a condition to allow live hydrogen reactant to be introduced for start-up.
- Part 3 - Latching solenoid hydrogen valve. The latching hydrogen valve isolates the reactant supply from the fuel cell stacks. The valve is actuated during automatic and manual shutdowns and during start-ups.
- Part 4 - Hydrogen pressure regulator. The hydrogen regulator is referenced directly from the fuel cell module oxygen reactant pressure and is designed to regulate H_2 4 psi below O_2 .
- Part 5 - Hydrogen check valves. The hydrogen check valve prevents propagation of a failure from stack to stack through the hydrogen system. It also provides third level redundancy of oxygen feedback to low-pressure hydrogen reactant supplies.
- Part 6 - Evacuation valves - hydrogen. This valve provides a means of clearing oxygen from the stack hydrogen system to vacuum in preparation for start-up.
- Part 8 - Coolant accumulator. The coolant accumulator provides a volume for the expansion and contraction of the coolant fluid. It is also utilized to control the coolant system pressure as it is referenced directly from the module oxygen pressure.
- Part 9 - Coolant pump and meter. The coolant pump circulates coolant water through the fuel cell module at 4.5 gpm and 11 psid.
- Part 10 - Thermal control valve. The thermal control valve controls the fuel cell module inlet coolant temperature at a nominal 150°F.
- Part 12 - Coolant heat exchanger. The heat exchanger provides the means of transfer of fuel cell module waste heat to the orbiter coolant fluid.
- Part 13 - Coolant overtemperature switch. The overtemperature switch initiates a module automatic shutdown at coolant outlet temperatures above 180°F.

Part 14 - Latching solenoid oxygen valve. This oxygen valve isolates the fuel cell module from the oxygen reactant supply. It is actuated during start-up, shutdown and leakage testing.

Part 15 - Purge valves - oxygen. This valve is periodically actuated to purge inerts from the cathode cavities of the fuel cell stacks.

Part 17 - Oxygen inlet check valve. This valve protects the low-pressure oxygen reactant from back-flow contamination.

Part 18 - Latching solenoid valve - product water. The product water valve isolates the fuel cell module product water system from the orbiter water system during shutdown periods.

Part 19 - Product water pressure regulator. The water regulator is referenced from the module oxygen pressure and regulates the water pressure at 3 psi below oxygen. This provides the driving force to remove the water from the module.

3.7

Performance Test Valves and Regulators

The fuel cell module hydrogen components were assembled in an operational subsystem that simulated actual fuel cell module conditions. See Figures 13 thru 15. This subsystem was operated for 2000 hours utilizing the hydrogen reactant at pressures, temperatures, flows and humidity conditions anticipated in actual use. Simulated stop/starts were performed on a weekly basis during the test period. Operational parameters were measured on a daily basis with component leakage and functional tests performed between missions. No test anomalies were observed. The items tested were:

- . Hydrogen regulator
- . Hydrogen check valve
- . Transducers
- . Hydrogen evacuation valve
- . Pressure switch
- . Hydrogen latch solenoid valve

The fuel cell module oxygen and product water components were assembled in an operational subsystem that simulated actual fuel cell module conditions. See Figures 16 thru 18. This subsystem was operated for 2000 hours, utilizing the oxygen reactant and water at pressures, temperatures, flows and humidity conditions anticipated in actual use. Simulated stop/starts were performed on a weekly basis during the test period. Operational parameters were measured on a daily basis with component leakage and functional tests performed between missions. The items tested were:

- . Oxygen latch valve
- . Transducer
- . Oxygen purge valve
- . Water regulator
- . Oxygen check valve
- . Water latch valve

Two anomalies were encountered during the oxygen/product water subsystem test. The first was detected during leakage tests after 250 hours of test. The development of a minor leak between oxygen and water was located in the product water regulator. Following disassembly of the regulator, it was determined that the source of leakage was through the bellows at a point of corrosion from the oxygen side. Improved methods of providing corrosion protection to the stainless steel bellows are under investigation. The second minor anomaly was detected in the oxygen latch valve during functional tests after 1800 hours. The valve exhibited both open and closed light indications when powered open. The valve problem was eliminated by reworking the valve stem to remove a tolerance stackup condition.

The fuel cell module coolant components were assembled in an operational subsystem that simulated actual fuel cell module conditions. See Figures 19 thru 21. This subsystem was operated for 2500 hours with distilled water coolant. The subsystem included a fuel cell module simulator with volumes, materials, surface areas, and waste heat simulations of the 5 KW fuel cell module. Simulated stop/starts were performed weekly for the first 2000 hours of testing. No test anomalies were observed. The items tested were:

- . Coolant accumulator
- . Coolant pump
- . Thermal control valve
- . Coolant heat exchanger
- . Coolant overtemperature switch
- . Pressure transducers

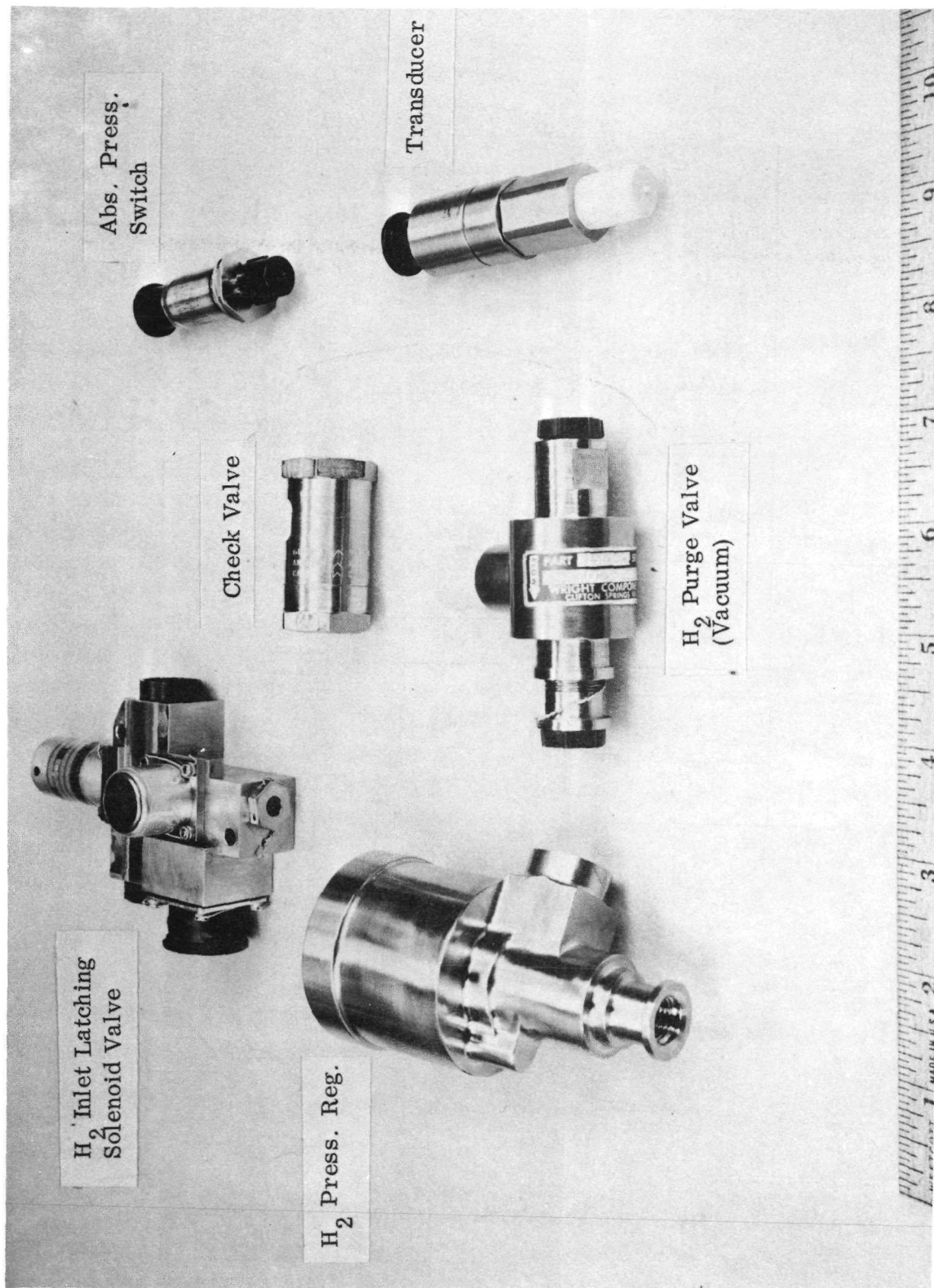


Figure 13. Hydrogen Subsystem Components

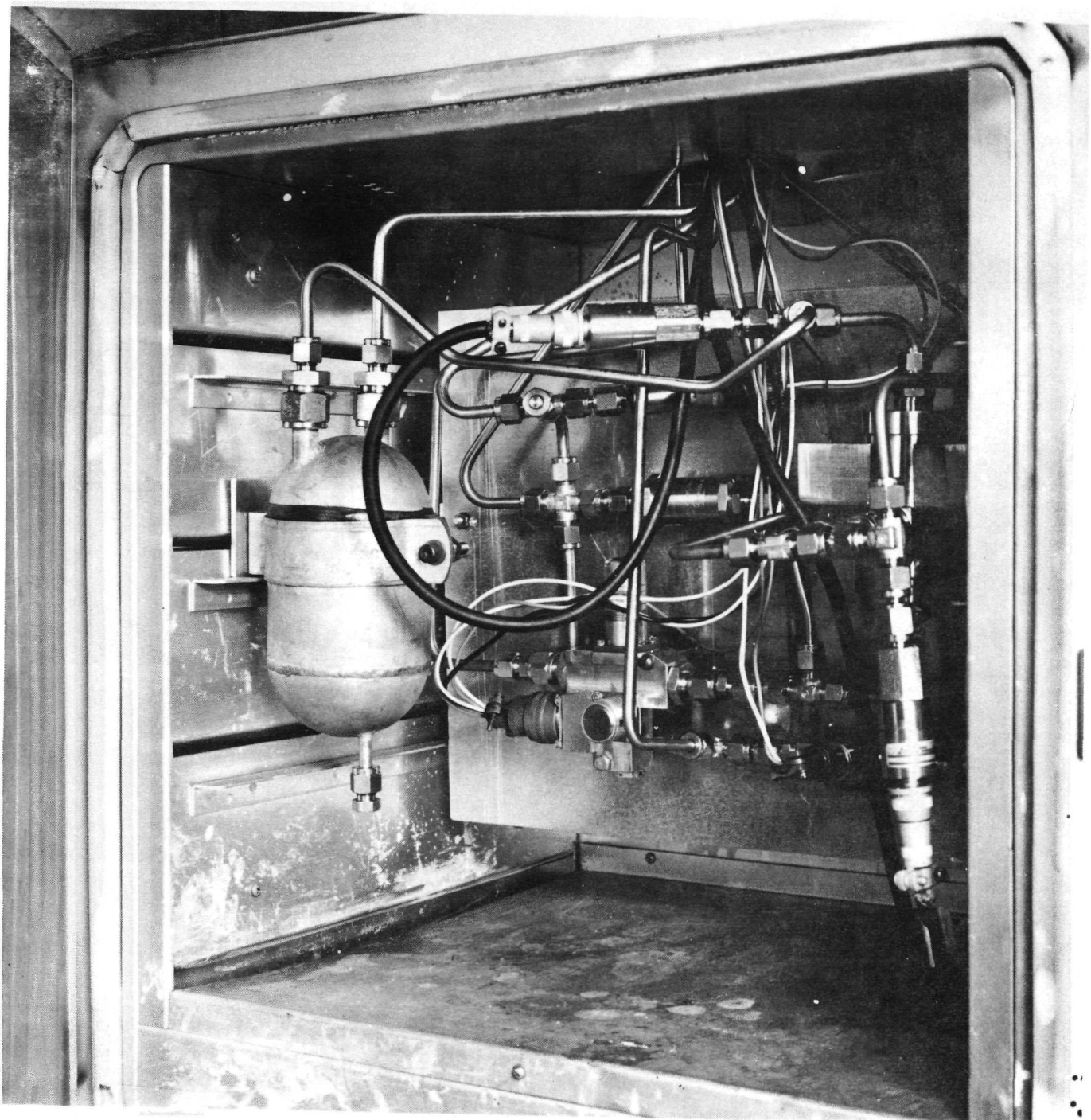
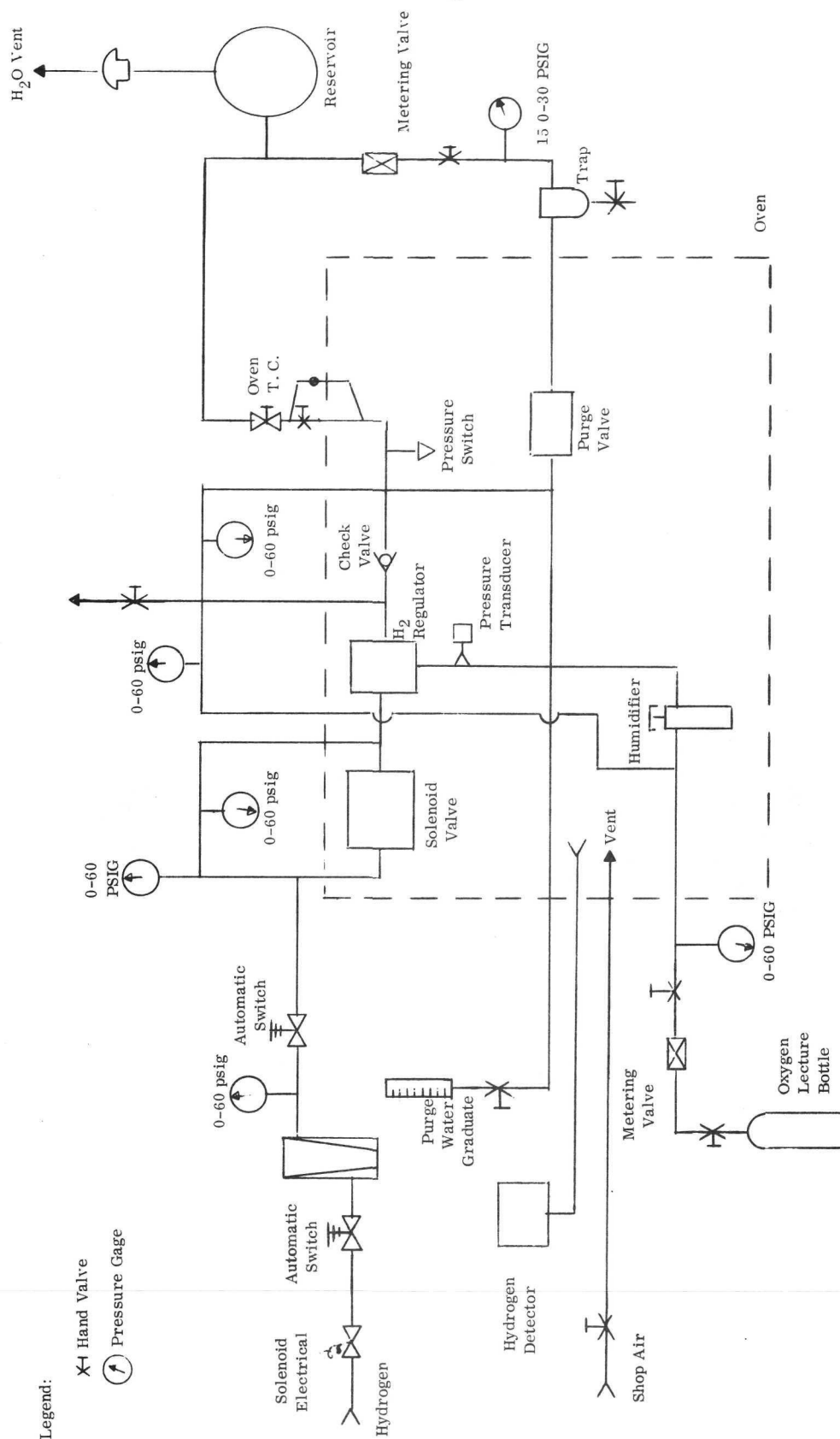


Figure 14. Hydrogen Subsystem Components Mounted in Oven



Legend:

✕ Hand Valve

Ⓢ Pressure Gage

Figure 15. Hydrogen Subsystem Life Test Schematic

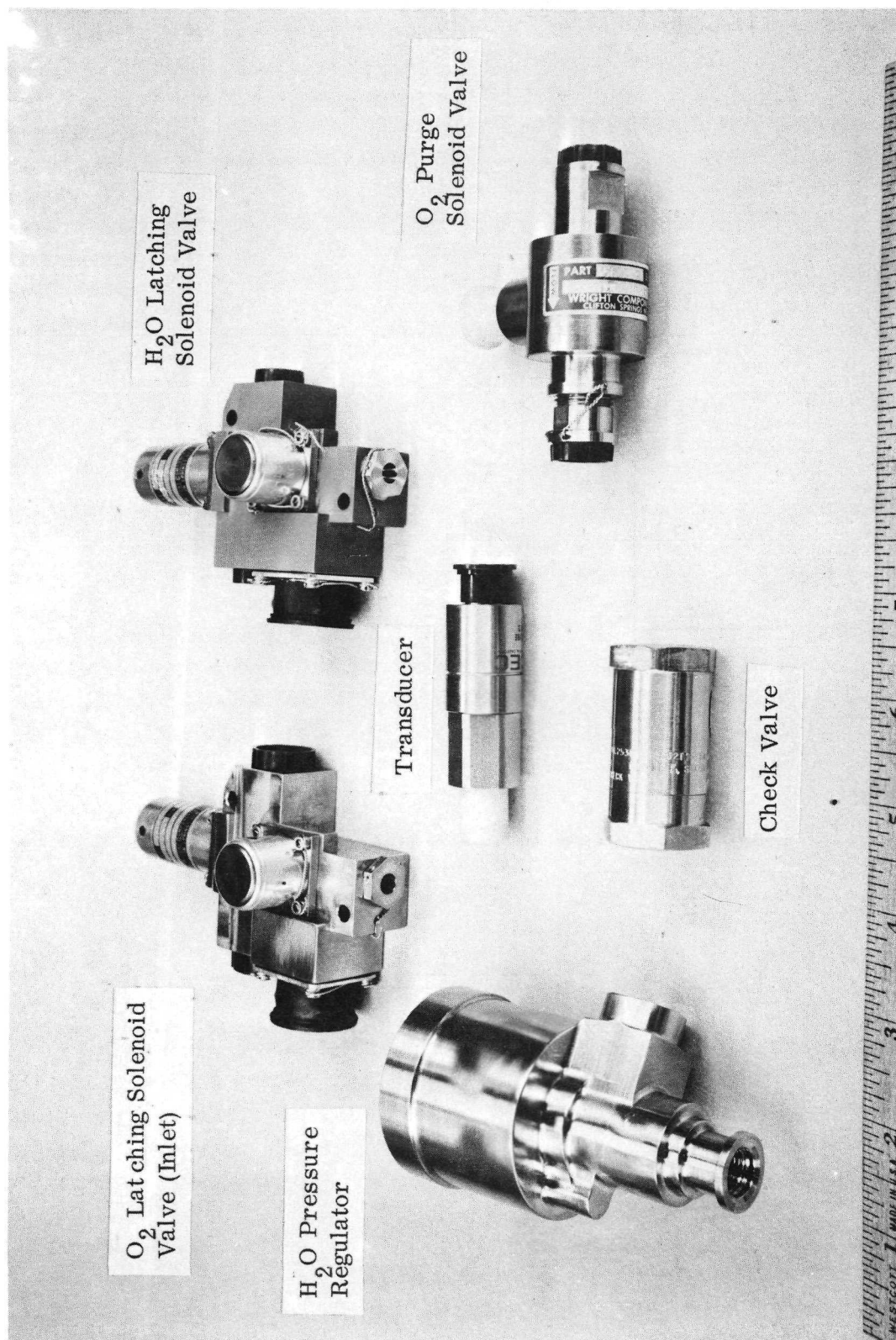


Figure 16. Oxygen and Product Water Subsystem Components

SPACE SHUTTLE
OXYGEN & PRODUCT WATER
SUBSYSTEM LIFE TEST
TOTAL HOURS 1460
CYCLE 9

6 28 71

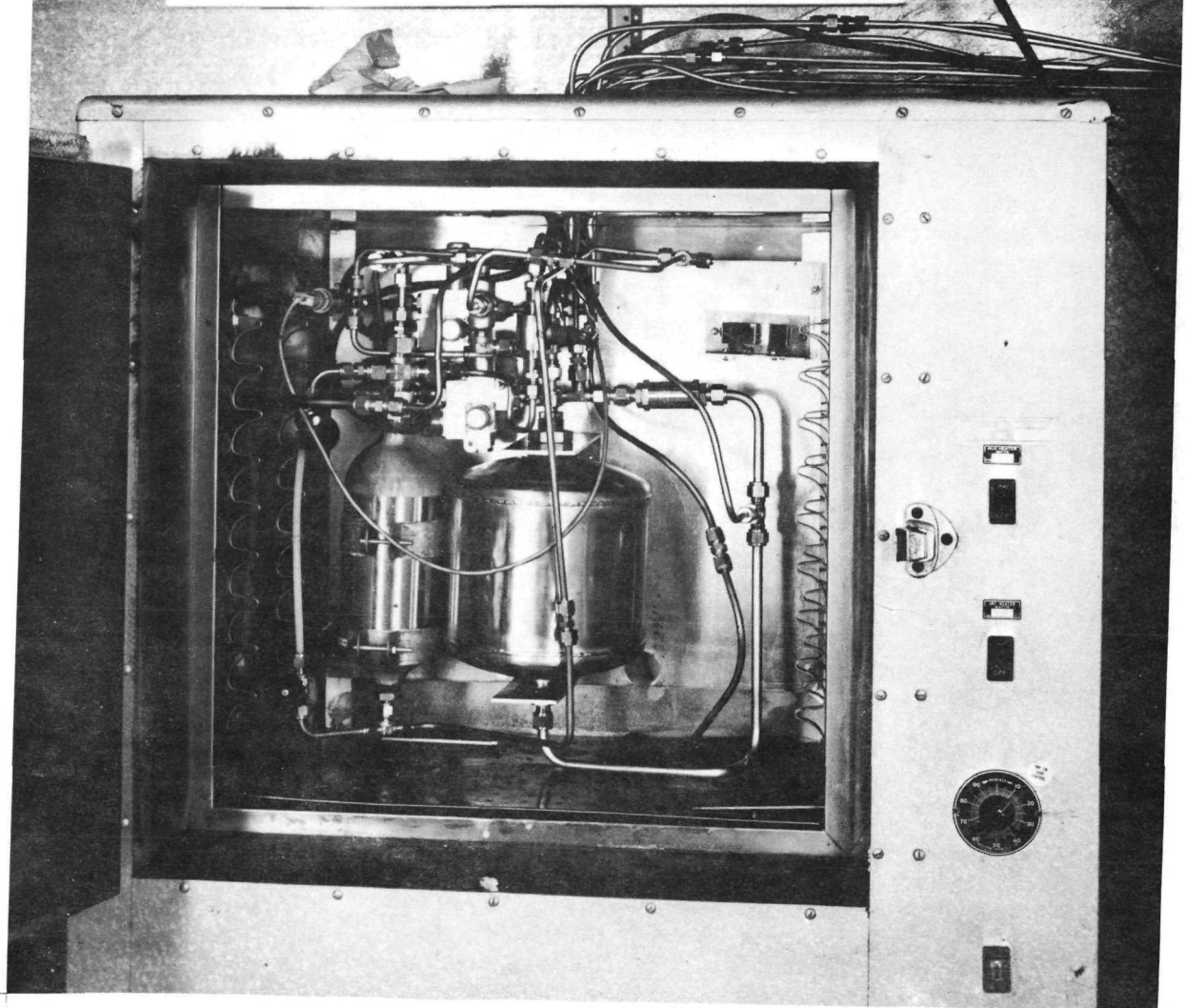


Figure 17. Oxygen and Product Water Subsystem Components Mounted in Oven

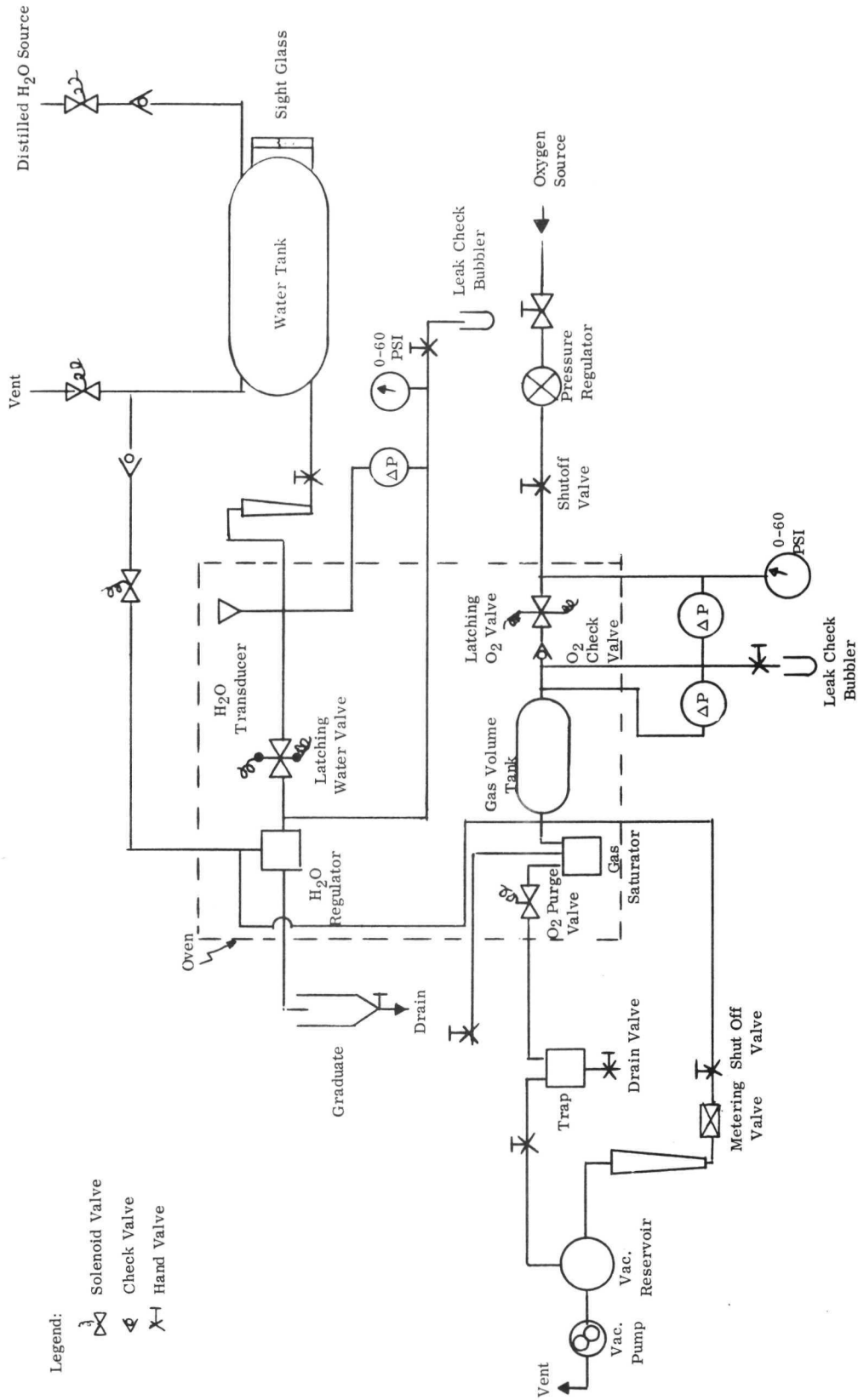


Figure 18. Oxygen and Product Water Subsystem Life Test Schematic

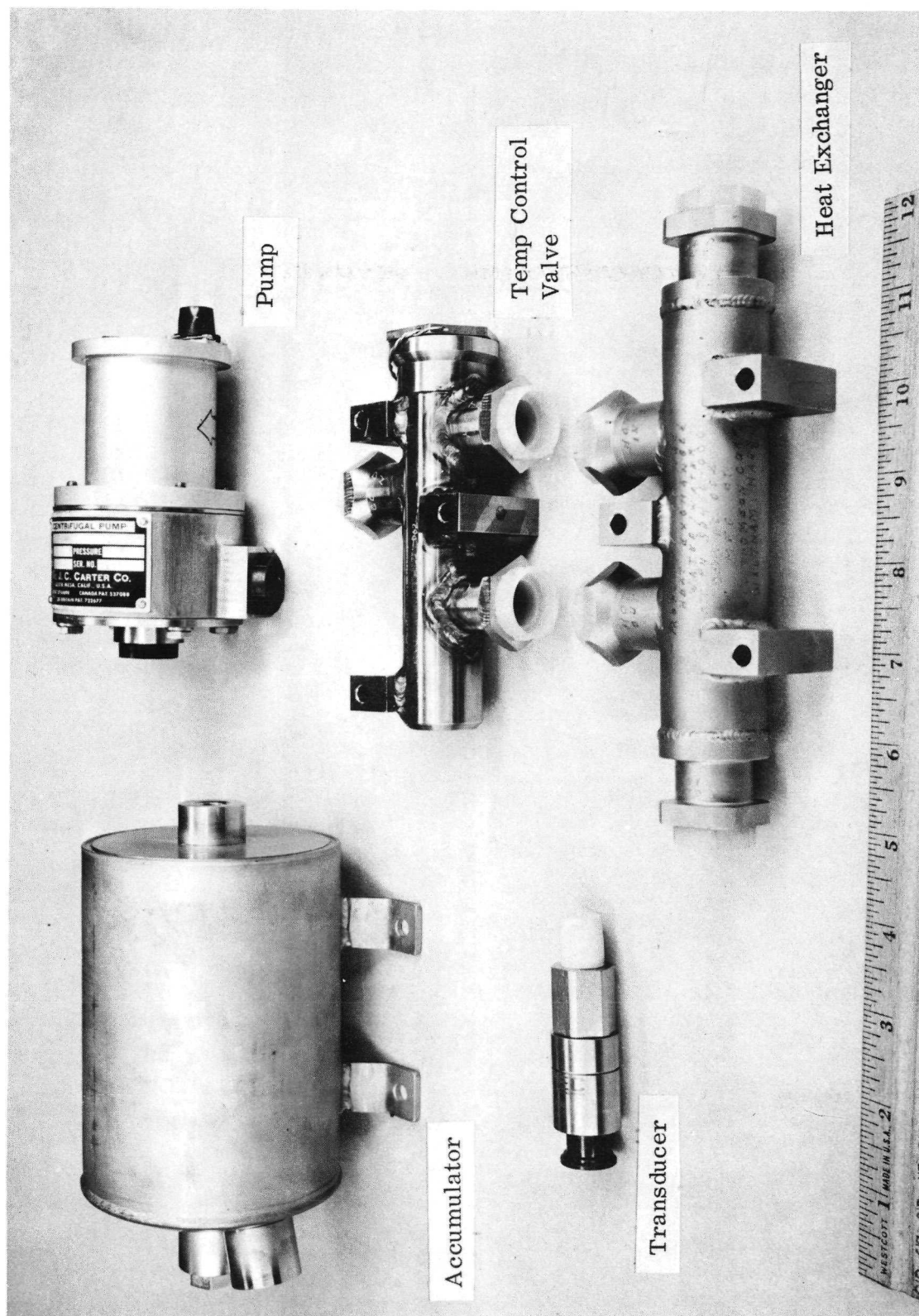


Figure 19. Coolant Subsystem Components

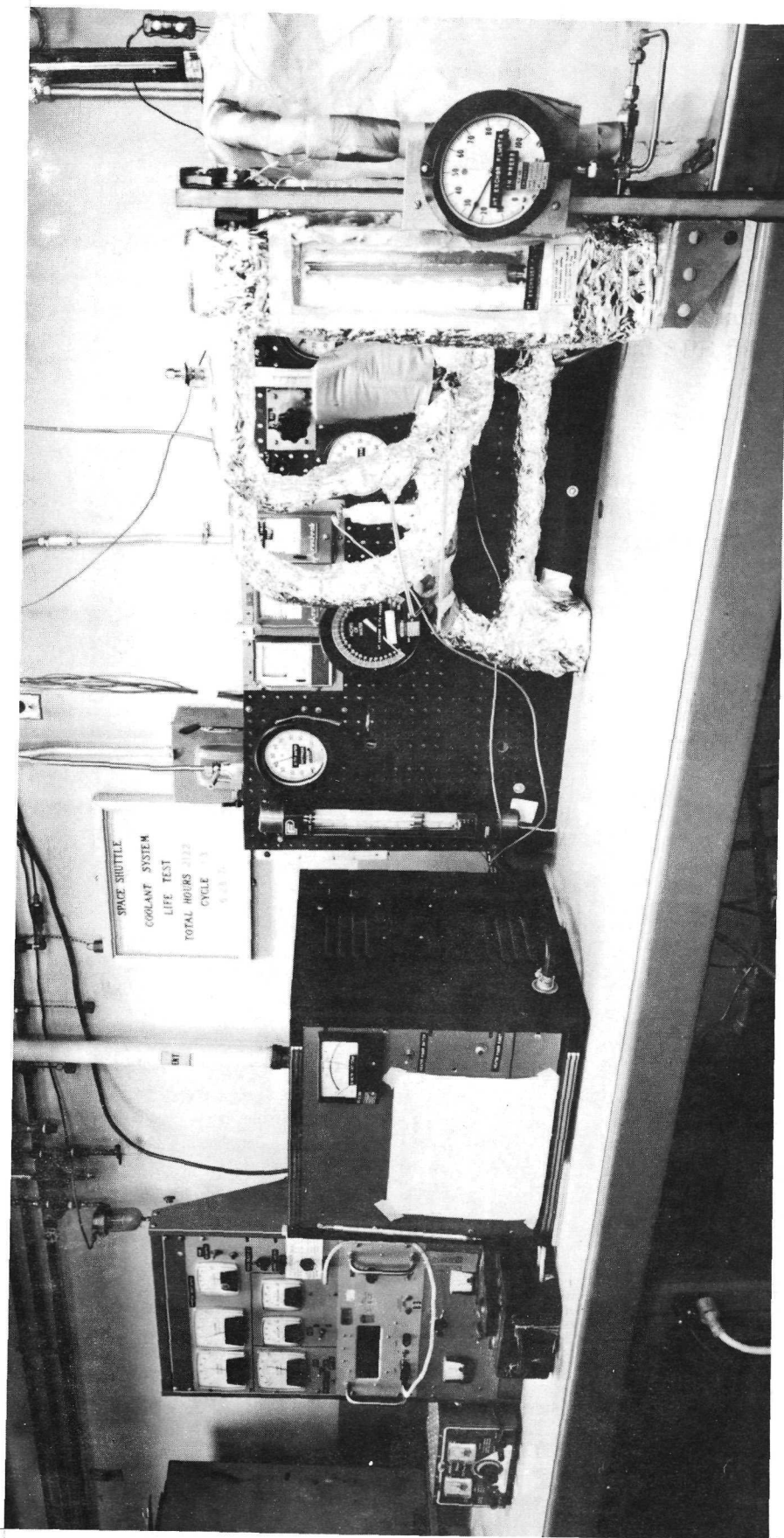


Figure 20. Insulated Coolant Subsystem Components Mounted on Test Bench

Legend:

- ✕ Hand Valve
- ◊ Check Valve
- ⊙ Pressure Gage

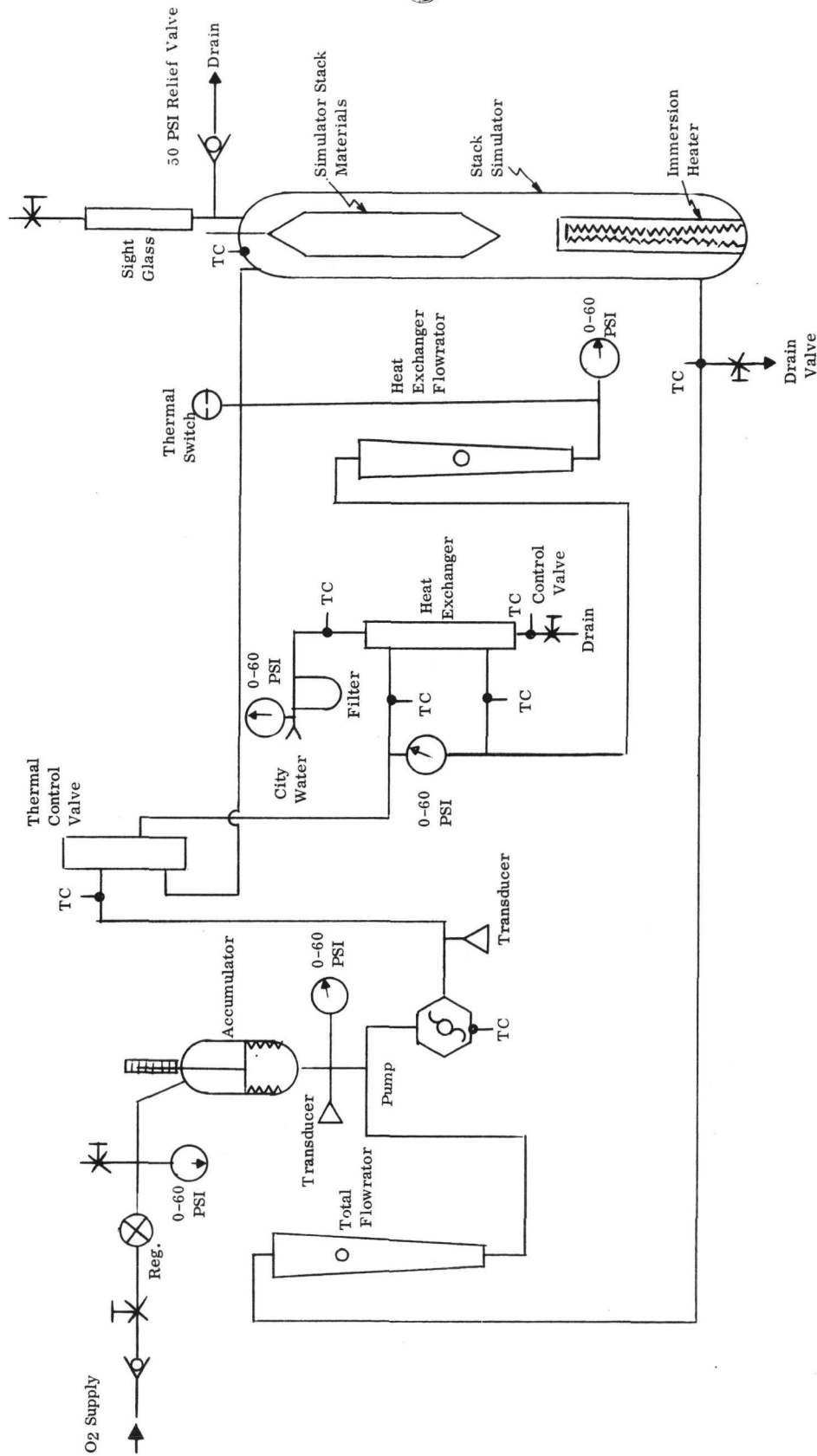


Figure 21. Coolant Subsystem Life Test Schematic

3.8

Cell and Stack Testing

Fuel cell testing was conducted with the test unit installed in a modular test case. Figure 22 shows a multi-cell fuel cell buildup partially assembled to a test case end plate. The test unit is installed in a test bay as shown in Figures 23 and 24. These bays are equipped for both manual and automatic operation and data recording. Figure 25 is a schematic of a typical SPE fuel cell test facility.

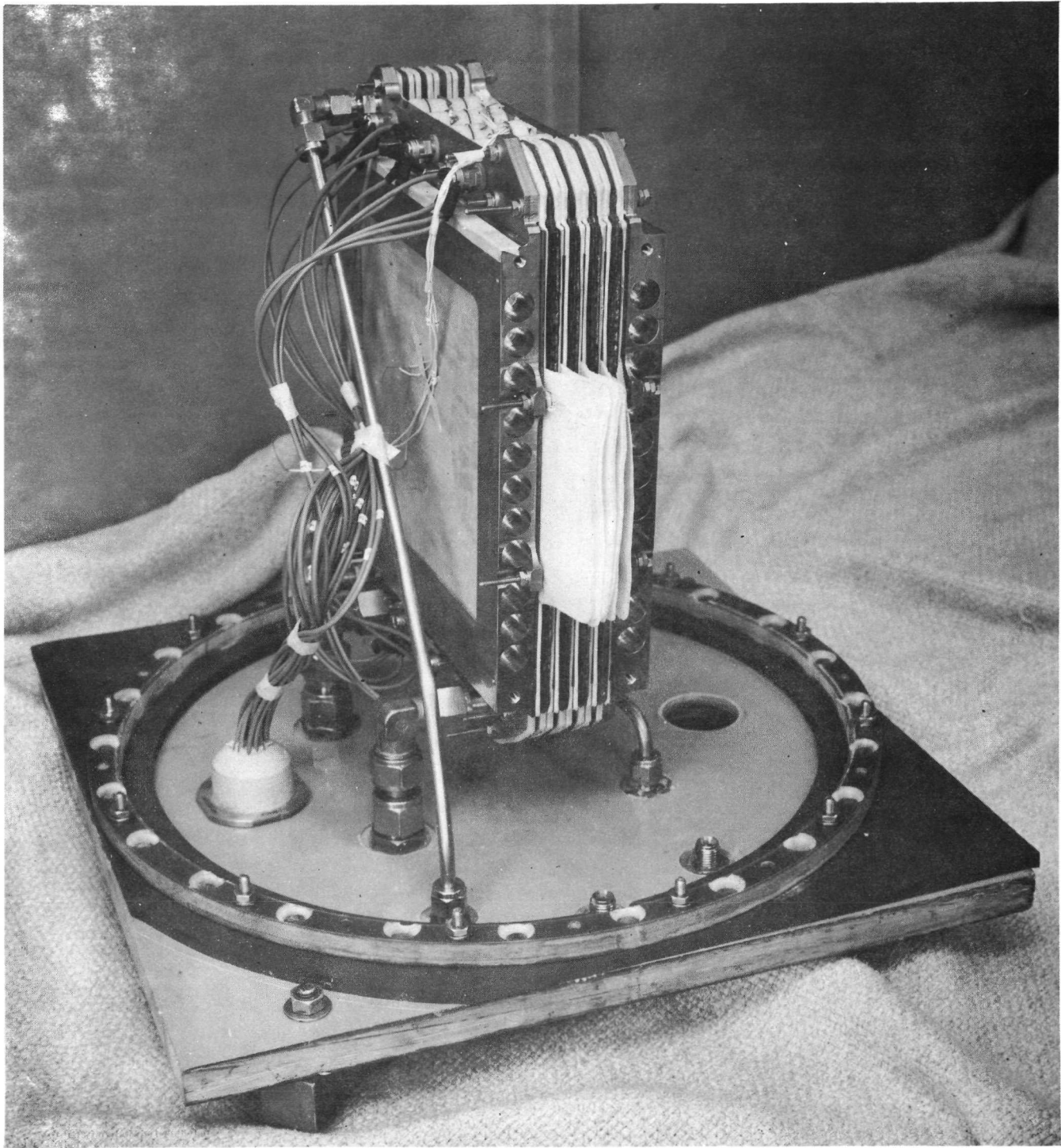


Figure 22. Multi-Cell Fuel Cell Buildup Partially Assembled to Test Case

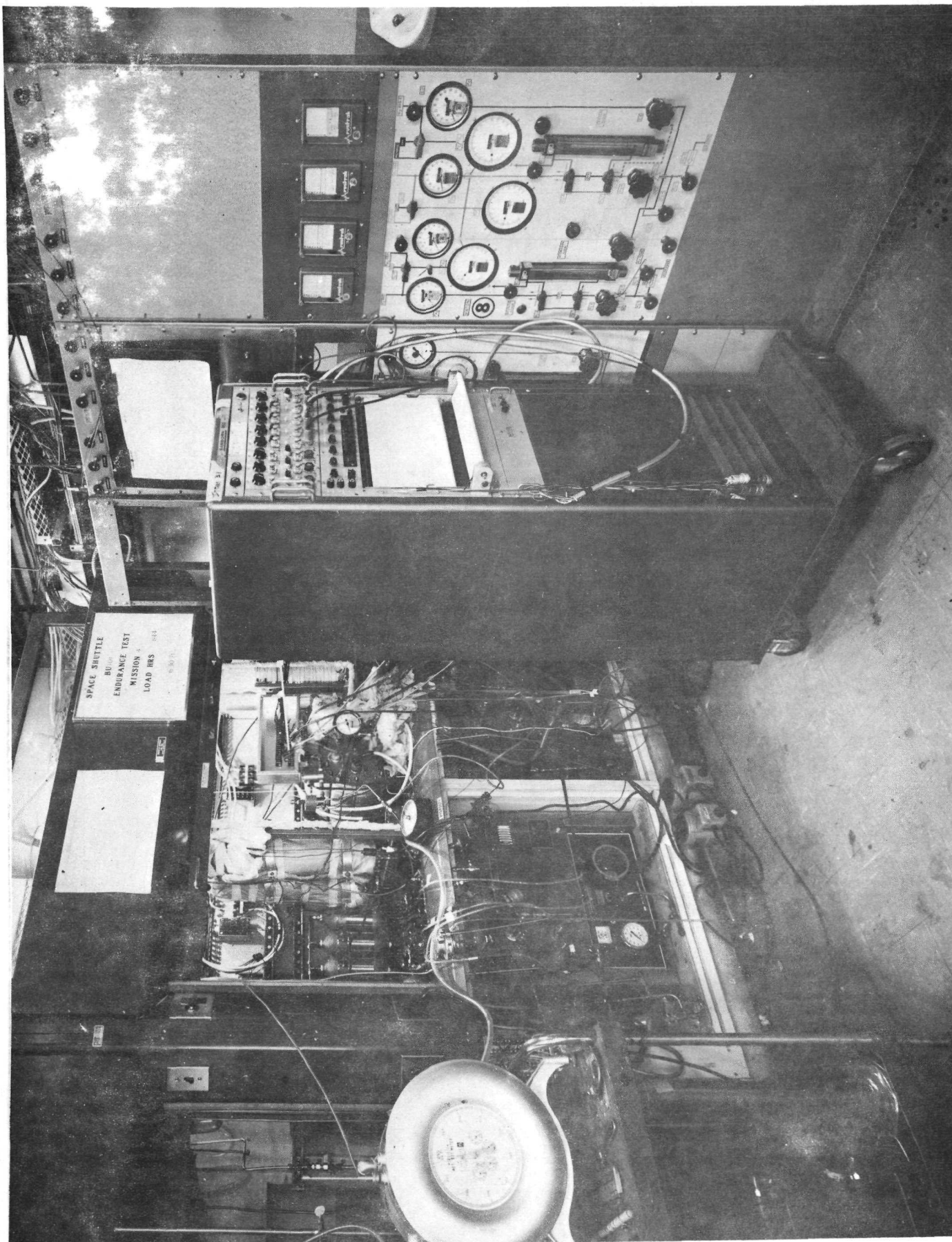


Figure 23. Fuel Cell Test Setup

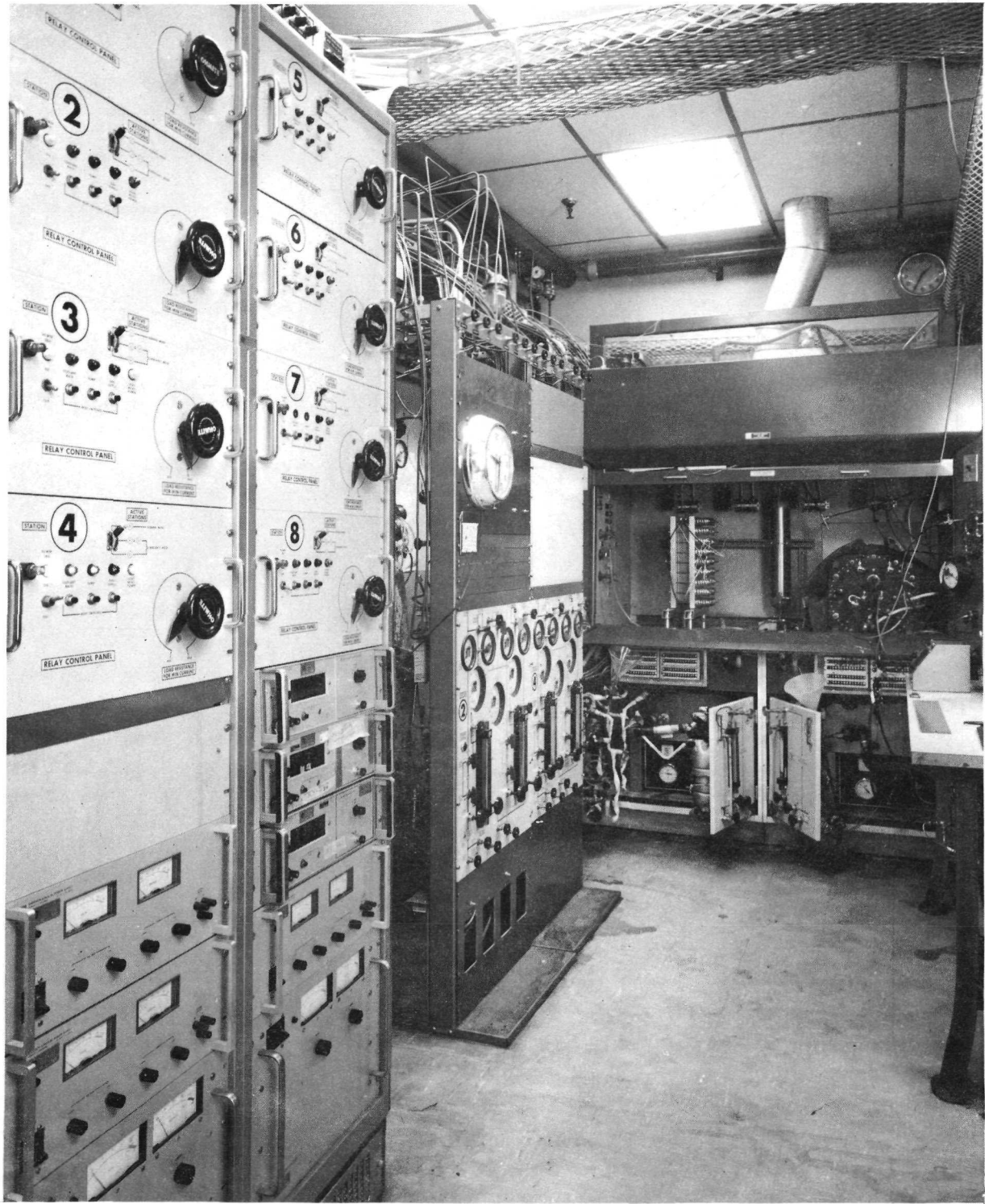


Figure 24. Fuel Cell Test Equipment

3.8.1

Buildup No. 1

The first Space Shuttle testing consisted of an 8-cell (four cell assemblies) small stack buildup designated Buildup No. 1. The unit was sent to test on 2 October 1970, incorporating all of the original Space Shuttle design concepts.

The design of B/U 1 incorporated four modifications intended to extend fuel cell operational life, two modifications to improve cell-to-cell performance uniformity, and two modifications aimed at reducing manufacturing costs. The modifications for the purpose of extending fuel cell operational life were:

- . Introduction of extruded "stabilized" "R" SPE.
- . Introduction of a peroxide decomposition catalyst within the SPE.
- . Introduction of a bond primer.
- . Elimination of the hydrogen purge manifold within the cell assembly.

The extrusion process of stabilized "R" SPE is a recent duPont development which resulted in a 30 to 50% increase in strength and an increased elongation from 50 to 70% to over 100%. The prime failure mode of the fuel cell during the B/U 1 design time period was considered to be SPE fatigue failure as a result of SPE water gradients as created by high current densities. The increased strength of the extruded SPE, along with reductions in average current densities, were introduced to extend the time for SPE fatigue to produce a fuel cell failure. GE/DECP drawing 1076527-732 introduced the extruded SPE.

A minor life-limiting mechanism was considered to be the release of small amount of HF from the "R" SPE, resulting in minor strength reduction. In addition, the HF released attacked some of the fuel cell stack assembly construction materials, such as the porous glass separator. GE/DECP developed a technique for further stabilizing the "stabilized" extruded "R" membrane by placing a peroxide decomposition catalyst within the SPE. This peroxide decomposition catalyst was introduced into B/U 1 by Manufacturing Process No. 000-102 as referenced on GE/DECP drawing 1076527-732.

During the earlier AFAPL cell development program, bond failures were identified as the major cell failure mechanism. This resulted in an exhaustive bond evaluation program. AF-42 bond tape, a product of Minnesota Mining and Manufacturing Co., was identified and successfully introduced into hardware. Continued evaluation of bonding systems identified Davon-24 bond primer as increasing the AF-42 operational life. This primer was introduced into all the AF-42 bond joints. The following GE/DECP drawings introduced the primer into B/U 1:

1076527-736, Cartridge Spacer Assembly

1076527-742, Cartridge Spacer and Cover Assembly

1076527-738, Coolant Cartridge Assembly

1076527-735, M and E Frame to Coolant Cartridge Assembly

1076527-749, Cell Assembly

The amount of dry hydrogen reactant passing over the SPE-electrode assembly at the inlet area was considered, at the time, to have a minor contribution to drying stresses resulting in fatigue failures. In the AFAPL fuel cell design, the two SPE-electrode assemblies on a coolant cartridge were fed hydrogen from a single slot manifold. On the opposite side of the cell, a second slot provided purge capability for the hydrogen cavities of each SPE-electrode assembly. The pressure drop during non-purge conditions was so low within the hydrogen distribution screens that the feeding of hydrogen to both SPE-electrode assemblies through the inlet of one SPE-electrode was very possible (i.e., a few drops of water could cause the restriction with no ΔP to drive the water out).

Since it was demonstrated both in the AFAPL and Hard Rock Silo development programs that hydrogen purging to remove inerts was unnecessary, the hydrogen purge slot manifold was removed from B/U 1 cell assemblies, thus producing dead-ended hydrogen gas spaces and preventing excess hydrogen from passing over the inlet area of one of the SPE-electrode assemblies. GE/DECP drawing 1076527-738 introduced the single hydrogen inlet slot manifold.

The two design modifications introduced into B/U 1 to improve cell-to-cell performance uniformity were:

- . Introduction of a porous Teflon film as a cathode wetproofing.
- . One edge product water removal with resultant 3-sided gas seal.

During the AFAPL program, it was observed that the cell-to-cell operational performance variations were greater than could be explained by internal impedance differences. It was concluded that these variations resulted from inconsistencies in the sprayed Teflon cathode wetproofing. Too much Teflon impeded the flow of oxygen to the reaction points and water removal, while too little Teflon allowed flooding of the electrode after extended life, thus producing a performance decay.

It was concluded that a pre-formed porous Teflon sheet would result in improved cell-to-cell performance uniformity. The porous Teflon sheet could be checked for pore size and flow rate prior to application to the cathode electrode. The

porous Teflon film was introduced into B/U 1 via M. P. No. 000-066 and GE/DECP drawing 1076527-732.

The AFAPL stack assembly employed a gasketed labyrinth screen assembly adjacent to each SPE-electrode assembly face. The screen assembly, when compressed within the stack, provided integral manifolding for O_2 , H_2 and coolant, O_2 distribution within the cell and a path for product water removal. Product water was removed by wicks which passed under the gasketed labyrinth screen assembly on two opposite sides of the stack. When the fuel cell operated, the inert gases within the reactants collected in the purge corner of the oxygen labyrinth. When a purge of the oxygen system was conducted, a large concentration of inert gas was ejected. However, in the purge corner of the labyrinth, the wick passed under the gasket making an imperfect gas seal. This imperfect seal resulted in requiring higher volumes of purge gases than would normally be required because fresh oxygen was passing through the imperfect wick seal and out the purge rather than through the labyrinth.

To obtain better inert removal and consequently improved cell-to-cell performance uniformity, B/U 1 was designed to remove all the product water from the oxygen inlet side, thus allowing a good gas seal on the oxygen purge side. In addition, the oxygen inlet was placed on the top of the cell such that product water had to be carried up to the separator to simulate the worst envisioned "g" loading condition. A double thickness of Dacron wicking was utilized for the water removal from each SPE and electrode assembly. GE/DECP drawing 1076527-753 is the gasket type utilized in B/U 1.

The two design modifications incorporated into B/U 1 for the purpose of reducing cell assembly costs were:

- . Catalyst load reduction.
- . Electrode collector bar reductions.

The AFAPL cell electrode structure utilized a catalyst mix loading of 33 gram/ft². Other projects utilized catalyst mix loadings down to 2 gram/ft² which gave cell performance improvements at high current densities and slight performance reductions at low current densities, with a crossover point at about 50 ASF. Electrode structures containing 4 gram/ft² catalyst mix were introduced into B/U 1. With a major portion of the catalyst mix being platinum, this resulted in considerable cost as well as weight reduction. Also, since the base load operation of the Space Shuttle cell was estimated to be about 57 ASF, no performance reduction was expected. The 4 gram/ft² catalyst mix was introduced into B/U 1 on GE/DECP drawing 1076527-732.

The AFAPL design incorporated 13 gold current collector strips into the electrode structure for the purpose of reducing the electrical resistance of the electrode. These collector strips were pressure-welded into a 3 mil thick/5 mil

strand gold screen to form the current collection structure of the electrode. The process of making the pressure-welded assembly was very time consuming. In B/U 1, 11 of the 13 collector bars were removed while the electrical resistance was maintained by increasing the screen strand width from 5 to 7 mils. The reduction in number of bars greatly reduced the structure assembly time. The new structure was introduced into B/U 1 on GE/DECP drawing 1076527-732.

Activation and polarization tests showed that cell performance was about .05 to .08 volt lower than expected. Various activation procedures were performed on B/U 1 to improve cell performance without success. The life endurance testing was initiated utilizing the originally planned current densities. Performance remained invariant at each mission condition through three complete missions and into the fourth mission, when the failure of Cell No. 3 resulted in test termination at a total load time life of 807 hours.

A preliminary failure analysis indicated the failure cause to be most probably the mixing of hydrogen and oxygen external to the cell, followed by introduction into the cell and resulting in heat release and SPE melting and leaking. Corrective actions were introduced into B/U 2 to minimize the chance of external reactant mixing and to protect the cells if a small amount of mixing occurred. Support testing and analysis indicated that a major portion of the performance loss was attributable to the design modifications introduced into B/U 1. This support testing, along with further examination of non-failed cells from B/U 1, showed that the preliminary analysis conclusions were probably incorrect and that the B/U 1 failure was caused by SPE drying resulting in stress fatigue cracking. The failure analysis of B/U 1 is described in GE document SPR-019.

Corrective actions to minimize stress fatigue were partially introduced into B/U 3 in the form of high water content SPE and into B/U 4 in the form of compartmentalizing the hydrogen cavities and anode electrode changes. Corrective actions to improve performance in the form of increased catalyst loading and surface area were introduced into B/U 2.

The testing of B/U 1 successfully demonstrated the following:

- . Simple stop/start operation.
- . Ability to operate at low reactant pressures.
- . Invariant performance.
- . Ability to operate without hydrogen system purging.
- . Ability to operate in negative one "g" conditions.
- . Potable product water.

See Figure 26 and Tables II thru IV.

Configuration: Base Line Design

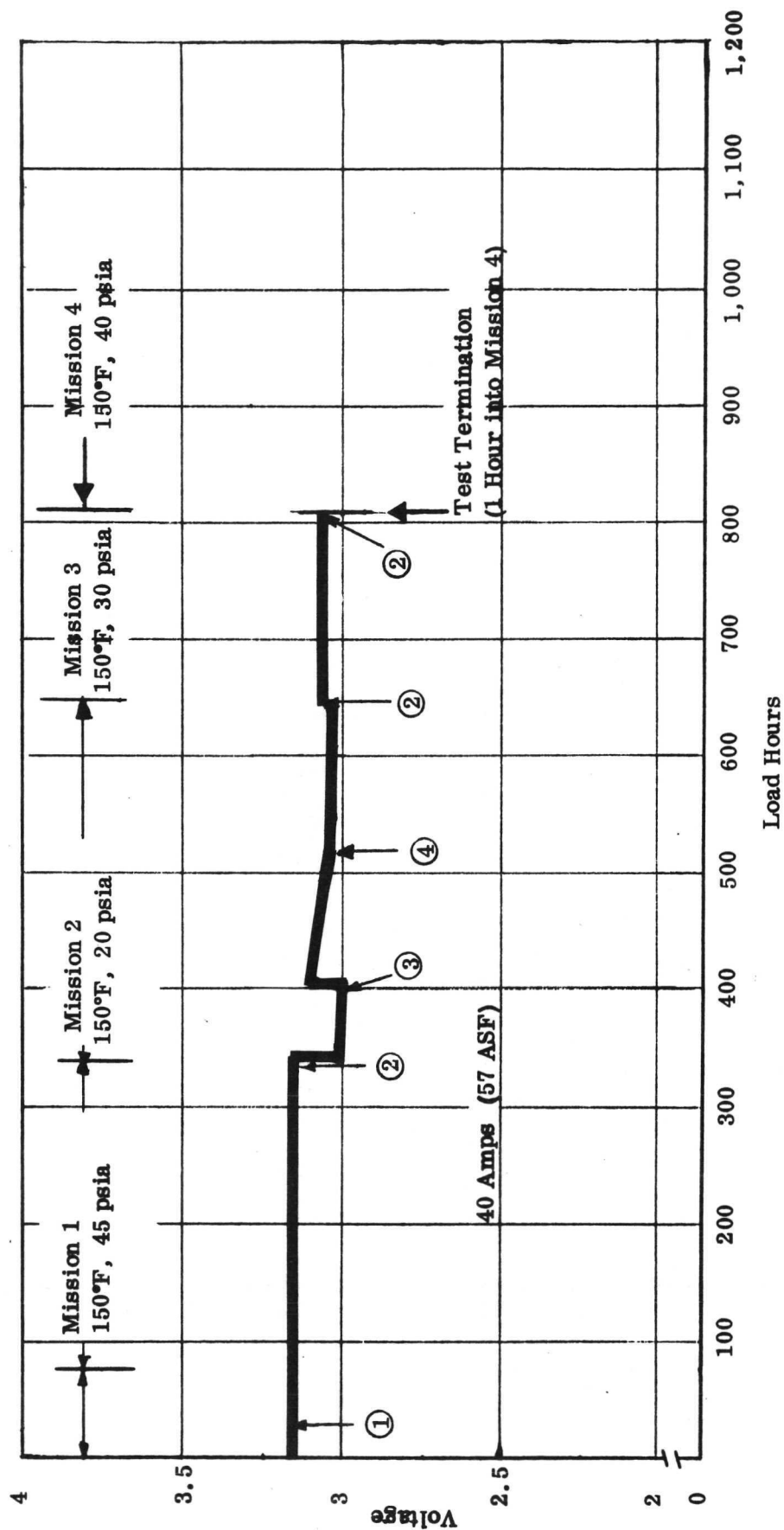


Figure 26. Buildup 1 Performance (8 Cells)

Table II

BACTERIOLOGICAL REPORT

GENERAL ELECTRIC FUEL CELL SAMPLE

Sample Number 1 Date October 30, 1970

Log-Book Number _____ Page Number _____ Load Hours 579

Program Space Shuttle Build-up

FINDINGS

Counts Per 100 ML of Water

<u>Time</u>	<u>Bacteria (2-10 ml)</u>	<u>Yeasts</u>	<u>Molds</u>	<u>Other (algae, lichens, protozoa)</u>
24 hr	0	0	0	0
3 day	3/10 4/10 35/100 ml	?	?	
7 day	same			Gram-neg non-spore forming bacteria in 7 original colonies
10 day	same			

NOTES ON GENERA AND, IF POSSIBLE, SPECIES

On this first run I put up samples as follows:

2 x 10 ml on 3rd day 3 and 4 colonies
1 x 1 ml on 3rd day 1 colony seen
1 x 0.1 ml
1 x 0.01 ml

Relatively low counts thru 3rd day are shown -- currently trying to identify species of bacteria found - will report later if successful.

Table III

BACTERIOLOGICAL REPORT
GENERAL ELECTRIC FUEL CELL SAMPLE

Sample Number 2 Date November 5, 1970
Log-Book Number SS B/U 1 Page Number 12 Load Hours 717
Program Space Shuttle

FINDINGS

Counts Per ML of Water

Time	Bacteria	Yeasts	Molds	Other (algae, lichens, protozoa)
24 hr	0	0	0	0
3 day	0	0	0	0
7 days	STILL NO GROWTH AT ALL			
10 days	STILL NO GROWTH AT ALL			

NOTES ON GENERA AND, IF POSSIBLE, SPECIES

On this run 4 x 10 ml samples were put up and 1 ml as a sheet anchor to wind ward.
No growth occurred on any of these; the cell, now, would appear to have less than 2
bacteria per 100 ml! (If any at all.)

Table IV

Product Water Analysis - Space Shuttle B/U No. 1

Constituent	ppm	Sample (Date/Load Hours)						Specification
		10/7/70 21 hr	10/9/70	10/20/70	10/21/70	10/27/70 504 hr	11/4/70 691 hr	
Total Solids	ppm	--	--	--	--	61.2	44.5	<500
Total Organics	ppm	--	--	--	--	29.4	15.0	--
pH		3.84	3.99	5.03	5.82	5.45	4.47	6.0-8.0
Color Units		0-5	0-5	0-5	0-5	0-5	0-5	15
Odor Threshold		1	1	1	1	1	1	3
Conductivity (μ mho/cm)		95.7	45.3	14.5	14.5	17.4	24.8	--
Arsenic	ppm	--	--	--	--	--	--	--
Cadmium	ppm	--	--	--	--	<0.01	<0.01	0.01
Chromium (+6)	ppm	--	--	--	--	<0.05	<0.05	0.05
Copper	ppm	1.44	0.32	--	--	0.07	0.01	1.0
Iron	ppm	--	--	--	--	<0.3	<0.3	0.3
Lead	ppm	--	--	--	--	<0.05	<0.05	--
Manganese	ppm	--	--	--	--	<0.05	<0.05	0.05
Magnesium	ppm	0.17	--	--	--	0.01	0.003	--
Potassium	ppm	1.81	0.27	0.06	0.06	0.15	0.14	--
Sodium	ppm	6.1	1.5	2.6	2.6	3.3	3.2	--
Sulfate	ppm	--	--	--	--	<2	<2	--
Cyanide	ppm	--	--	--	--	--	--	--
Fluoride	ppm	1.14	2.25	1.46	1.50	2.21	3.30	--
Titanium	ppm	--	--	--	--	<0.2	<0.2	--
Platinum	ppm	--	--	--	--	<0.05	<0.05	--
Chloride	ppm	11.8	2.40	1.86	1.75	1.39	<1	--
Silica	ppm	--	--	--	--	19.2	20.7	--
Silver	ppm	--	--	--	--	<0.05	<0.05	0.05
Mercury	ppm	--	--	--	--	<0.002	<0.002	0.005
Nickel	ppm	--	--	--	--	0.01	0.01	0.05
Zinc	ppm	0.65	<0.3	<0.3	<0.3	<0.3	<0.3	5.0

Micro-organisms cts/cc: Bacteria and Fungi - See attached sheets.

3.8.2

Buildup No. 2

The design of the cell assemblies for B/U 2 contained all of the features of those in B/U 1, namely:

- . Extruded stabilized "R" SPE.
- . Peroxide decomposition catalyst within the SPE.
- . Bond primer (Davon 24).
- . Elimination of H₂ purge manifold.
- . Porous Teflon film as cathode wetproofing.
- . One edge product water removal with resultant three-sided gas seal.
- . Anode catalyst loading 4 mg/cm².
- . Current collector bars on electrodes changed to just an edge frame.

One design modification was introduced in B/U 2 which was intended to improve performance. This was the increase in cathode catalyst loading from 4 to 8 mg/cm². In addition, the following design modifications associated with the final stack design for EM-1 were incorporated:

- . Lightweight end plates with titanium frame and honeycomb center plate. This design provides cell-to-cell electrical contact forces as well as manifold sealing forces.
- . All fluid ports on one end plate. This enables minimum volume installation of two stacks within the EM-1 container.
- . Simplified cell-to-cell electrical connections, incorporating longer bus bar tabs to allow direct cell-to-cell tab contact.
- . Alternate cell assemblies have bus bar tabs of opposite potential.
- . Redesigned O₂ frame assembly to include attached rubber compression springs to provide cell-to-cell electrical tab contact forces. Also added O₂ sealing beads to insure three-sided gas seal.
- . Tabs added to O₂ spacer to support electrical compression springs.
- . Lightweight and smaller product water removal system with single necked-down wick for each SPE-electrode assembly.
- . Eliminated tie rod stack compression springs to reduce weight and volume.

After the preliminary failure analysis of B/U 1 hardware, the probable cause of failure was suspected to be H₂/O₂ mixing within the H₂ system. The decision was made to install a catalytic burner in the H₂ inlet manifold of B/U 2 to insure uniform and safe reaction with H₂ if small quantities of O₂ are present. The configuration of this catalytic burner was approximately .125 inch diameter by 1.5 inch long and consisted of a rolled up strip of .002 inch thick platinum catalyst blend reinforced with .002 inch thick gold screen. The catalyst mix loading was 22 mg/cm². This small roll of electrode was inserted in the H₂ inlet manifold behind the H₂ inlet fitting.

The stack of four cell assemblies was then installed into a high-pressure test case with the water system at the top of the stack.

The following detail and assembly drawings describe the configuration of B/U 2:

<u>Title</u>	<u>GE/DECP Drawing No.</u>
M and E Assembly	1076527-751
Cell Assembly	1076527-752
O ₂ Frame Assembly	1076527-757
O ₂ Frame, Wick and Screen Assembly	1076527-754
Spacer Assembly	1076527-755
End Plate Assembly	1076527-767
Stack Assembly - 4 Cells	1076527-769

B/U 2 was ready for endurance testing on 13 November 1970. The decision was made to operate at the same conditions of temperature, pressure and electrical load as used in the testing of B/U 1 instead of the previously planned higher temperature, pressure and load (refer to Small Stack Test Plan, SPR-007, dated 21 August 1970).

Initial B/U 2 activation was conducted on 16 November 1970. The electrical performance was observed to be only slightly improved over that of B/U 1. Various activation procedures were ineffective in increasing performance levels and the corrective actions taken as a result of B/U 1 low performance were not effective.

Three simulated missions were completed with the modified stop/start following each mission. Performance during each mission was stable. After 70 hours into Mission 4, a slightly low voltage of cell 3 following oxygen purge rate adjustments was observed. A manual shutdown and leakage check confirmed an abnor-

mal oxygen-to-hydrogen system leakage rate. Testing of the buildup was terminated to determine the location and nature of the excessive leakage. Total operational time at test termination was 892 hours. See Figure 27 and Table V.

A teardown and preliminary analysis was performed on B/U 2. This analysis concluded that the most probable cause of failure was stress fatigue cracking at the oxygen inlet due to drying of the SPE which allowed oxygen into the anode compartment, partially discharging the cell. The lack of sufficient water available from the wicking in the area of the oxygen inlet due to the change in the wick configuration was concluded to be the cause for allowing the excessive drying of the SPE in this area. The test report covering B/U 2 is given in GE document SPR-036.

B/U 2A was constructed using two of B/U 2 unfailed cells. The failure of this buildup in the same manner after only two hours of additional test confirmed the preliminary conclusions.

A matrix of laboratory 3 x 3 inch fuel cell tests was performed to identify the nature of the performance problem. These tests utilized various B/U 2 type materials to attempt to "contaminate" the cells and produce lower performance. AF-42 bonding film resulted in performance losses that amounted to 25 - 40 millivolts per cell.

Corrective actions to minimize stress fatigue were introduced into the oxygen system of B/U 3 and into both oxygen and hydrogen systems of B/U 4. No corrective actions were introduced to eliminate bond film contamination as a suitable non-contaminating replacement for the AF-42 adhesives has not been identified. Analysis of potential replacement bond materials was deferred to a follow-on program scope.

The B/U 2 testing successfully demonstrated the following design modifications: lightweight end plates; compression electrical connections; compression springs eliminated; and, smaller water separator.

Configuration: Base Line Design

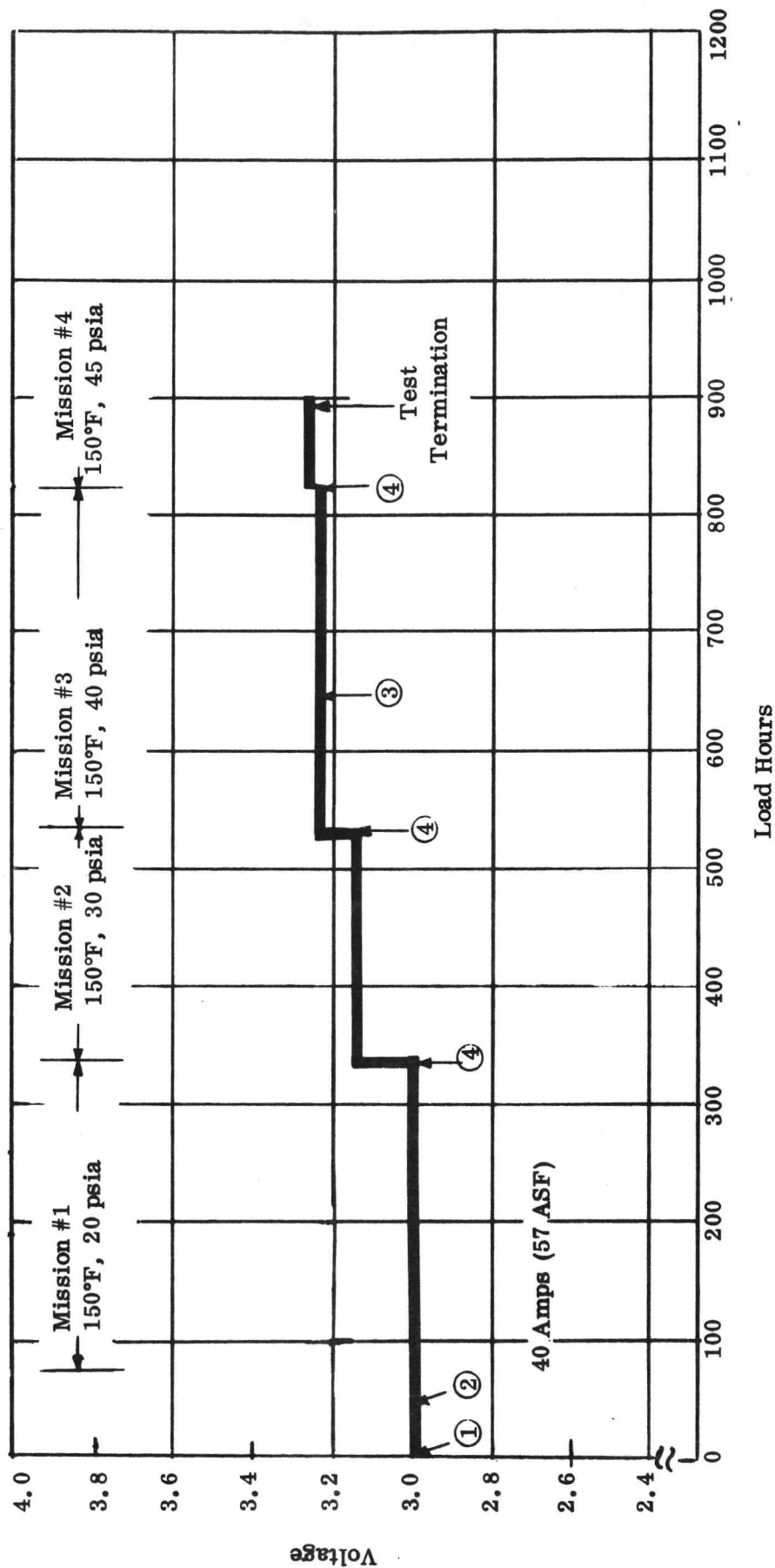


Figure 27. Buildup 2 Performance (8 Cells)

- ① Deep Discharge
- ② Electrolysis
- ③ Coolant Pump Failure
- ④ O₂ Takeover with Vacuum Purge

Table V

Concentration (mg/L) of Constituents Present in B/U 2 Product Water

<u>Constituent</u>	<u>Time (hours)</u>						<u>Specification</u>
	<u>70</u>	<u>170</u>	<u>268</u>	<u>425</u>	<u>658</u>	<u>822</u>	
Total Solids*	97	37	21	27	31	27	<500
Total Volatiles	53	17	5	7	12	7	-
Non-Volatile Solids**	44	20	16	20	19	20	-
Silica	21	14	-	-	-	-	-
Potassium	4	0.38	0.36	0.50	0.54	0.33	-
Sodium	7	1	1	1.1	0.5	1.3	-
Chloride	15	26	11	1.0	-	-	-
Fluoride	1.1	3.5	5.9	8.7	11	7.8	-
Iron	0.06	0.05	0.07	0.13	0.18	0.06	0.3
Copper	0.31	0.09	0.03	0.04	-	-	1.0
Zinc	0.42	0.06	0.03	0.06	-	-	5.0
pH	5.4	4.5	4.0	3.7	3.6	3.7	6.0-8.0
Bacteria (cts/ml)***	243 at 1,680 3,000 30,000 193 hr at 375 hr at 523 hr at 702 hr						TBD

* Dried at 110°C for 24 hours.

** Ashed at 550°C for 24 hours.

*** Bacteria identified as non-pathogenic yeast
 pulullaria pululans - air borne, dust inhabiting

3.8.3 Buildup No. 3

The Small Stack Test Plan, SPR-007, report dated 21 August 1970, outlined the original objectives of B/U 3 as being:

- . The evaluation of promising developments from the technology exploitation task.
- . The evaluation of product improvements resulting from B/U's 1 and 2.

The technology exploitation task centered around three potential improvements:

- . Modified molecular weight SPE for improved performance.
- . Coolant plates and screens of titanium-palladium for lighter weight.
- . Alternate materials for wicks and water separators for improved flow capability and better life stability.

The technology exploitation task (see Report SPE-026, dated 17 February 1971), was completed with the following conclusions:

- . SPE equivalent weight should be maintained at 1200 (0.83 IEC), but that extended life could be obtained by adjusting the SPE water content to 36-42 wt %.
- . Hydrogen embrittlement is a serious problem with Ti-0.2 Pd metal and therefore should not be used in the anode compartment of a fuel cell.
- . The porous glass separators and dacron wicking used on B/U's 1 and 2 were found to be the most compatible with fuel cell operating conditions.

The configuration of B/U 3 was originally conceived to have four cell assemblies, but was reduced to one when the unscheduled failure analysis of B/U 1 limited the available funds. The design of the B/U 3 hardware was similar to that of B/U 2 with the following exceptions:

- . The SPE water content was increased from 28 to 38 wt % as recommended in the Technology Exploitation Report (Manufacturing Process MP-000-110).

- . A catalytic scavenger was built into the anode frame to prevent failures from small amounts of reactant mixing (B/U 1 failure analysis recommendation).
- . The old style end plates were utilized as the new design was not suitable for a single-cell assembly.

B/U 3 was shipped to test on December 22, 1970, and was activated by the deep discharge method. Electrical performance of the buildup was similar to B/U 1 and 2.

Just after the testing of B/U 3 began, B/U 2 failed on December 24, 1970. The failure analysis that followed resulted in the conclusion that the failure cause was SPE cracking at the oxygen inlet area due to drying fatigue stresses imposed on the SPE and that this led directly to reactant mixing and depolarizing of the affected cell. The same type of stress was analyzed to have been at the hydrogen inlet area although that did not specifically result in the failure.

B/U 3 testing was terminated at 408 total hours for corrective action retrofit, as it was determined that it was also being subjected to the same drying stress fatigue that failed B/U 2.

Design changes were made on the oxygen side of the cell assembly only, as the bonded structure of the B/U 3 cell assembly was unsuitable for internal changes. The oxygen-side modifications included:

- . Added a second wick in the oxygen inlet area with the feed tube behind the wicks.
- . Removal of the O₂ labyrinth and Teflon screen.
- . Inverting the stack, with water removal at the bottom.

The buildup, using the original cell assembly, was designated Buildup No. 3A and sent to test on January 20, 1971.

Following two deep discharges, the performance of B/U 3A returned to the pre-retrofit level and continued there throughout the 2000 hour test. Eight simulated missions at pressure levels between 20 - 45 psia were performed with stop/starts between each mission during the 2000 hours. A slight increase in oxygen purge sensitivity was noted after mission startups for the last 500 hours of testing.

At the completion of 2000 hours of testing, an oxygen-to-hydrogen leakage test revealed a 4 times normal rate. An attempt at additional operation beyond 2000 hours resulted in an automatic shutdown from a low voltage signal at 2031 hours.

The O₂-H₂ leakage rate was then determined to be about 10 times normal. Total endurance test performance is shown in Figure 28.

The buildup was then disassembled to determine the location of excessive leakage. The leakage was identified within the bonding system with no through-SPE leakage evident. In addition, the water removal wicks were found in direct contact with the cathode assemblies due to removal of the screen labyrinth assemblies. It was concluded that the purge sensitivity during the last 500 hours and the final low voltage shutdown were the result of the bond leakage and/or the wick-cathode contact. The test report covering B/U 3 is summarized in GE document SPR-039.

Corrective action was demonstrated via laboratory testing on an improved membrane bond procedure. This procedure was introduced into B/U 101 (i.e., NASA Contract NAS 9-11876).

Although B/U 3/3A was only a one-cell assembly unit, it did demonstrate the basic inherent capability of the solid polymer electrolyte to perform in flight-type hardware.

Configuration: Base Line Design
High Water Content SPE
Modified O₂ Inlet

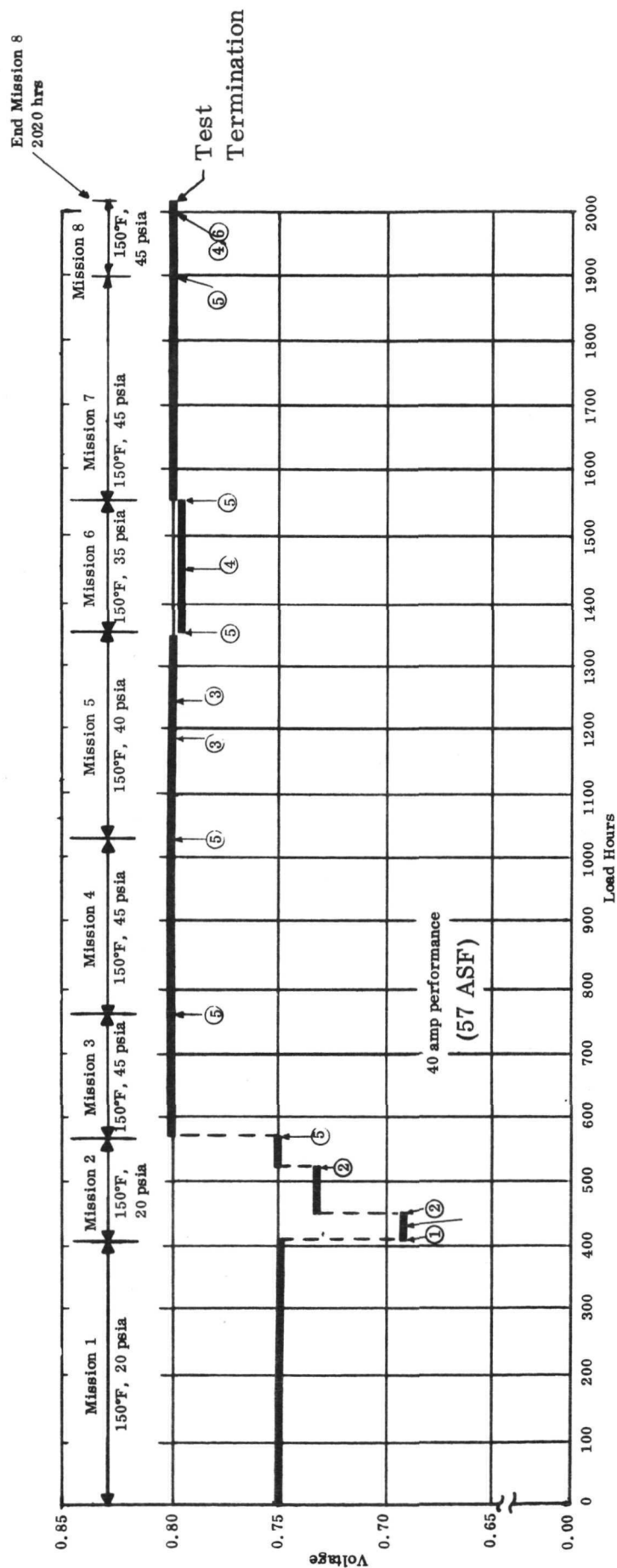


Figure 28. Buildup 3 Performance (2 Cells)

3.8.4

Buildup No. 4

After the failure analyses of B/U 1 and 2, several corrective action design changes were identified and incorporated into B/U 4 and 5. These changes consisted of the following:

- 1) Divide the hydrogen compartment into eight individual areas and add a second H₂ inlet channel to fully distribute the inlet H₂ flow and thus simulate the inlet conditions of the laboratory test fixture.
- 2) Modify oxygen inlet to bring the dry gas into the cell behind the product water wick, thus humidifying it before exposure to the SPE.
- 3) Increase catalyst loading on the anode from 4 to 30 mg/cm² to provide a mass transport barrier against water loss from the SPE.
- 4) Increase catalyst loading on the cathode from 4 to 8 mg/cm² to improve performance (B/U 5 was later reduced to 4 mg/cm² again).

All of the preceding modifications were incorporated into the design of B/U 4 which was manufactured with eight cells (four cell assemblies).

Cell Assembly Configuration

Compartmentalization of the H₂ cavity was accomplished by making the following changes:

- 1) Addition of a polysulfone grid pattern molded into the H₂ distribution screen (Dwg. 1076527-747).
- 2) Add a second H₂ inlet channel and manifold at top edge of cell assembly (Dwg. 1076527-738).
- 3) Add grid pattern to coolant cartridge plates to match pattern in H₂ distribution screen (Dwg. 1076527-744).

The revised configuration is designed to divide the H₂ compartment into eight 3.7 x 1.9 inch areas to duplicate the H₂ inlet conditions present in the 3 x 3 inch laboratory units. From the patterns of failures and delaminated SPE in B/U 1 and 2 it was concluded that all the H₂ was flowing over the bottom third of the cell. Since the active area of the 3 x 3 inch cell is .05 ft² compared with .375 ft² in the Space Shuttle cell, the H₂ flow velocity at the H₂ inlet of the Space Shuttle cell was approximately .375/.05 or 7.5 times that in the laboratory unit at any given current density.

In the revised design of B/U 4 and 5, flow of H₂ between the small compartments is minimized by the molded polysulfone ribs in the hydrogen screen assembly. Hydrogen flows into each small compartment from the top or bottom H₂ channel. Thus, the H₂ flow velocity over any given point on the anode is considerably reduced.

The catalytic scavenger introduced into the single H₂ inlet channel in B/U 3 was retained in both channels in B/U 4. Drawing 1076527-826 shows the configuration of the catalytic scavenger assembly.

Higher water content SPE (36 to 40 wt%) was incorporated into the SPE-electrode assemblies by the SPE autoclaving process developed for the B/U 3/3A cell.

Figure 5 shows the modifications to the SPE-electrode assembly and bonded joint was modified to separate the SPE bond stress condition from the H₂ inlet stress area. The width of the collector strips was increased from .060 to .125 inch so that the electrode screens could be terminated at the centerline of the collector strips. This effectively prevents the screen strands from overhanging the collector strips and puncturing the SPE during the bonding cycle.

The suspected high stress point at the inner edge of the SPE-electrode to SPE-electrode frame bond was considered to be too close to the H₂ inlet area and was also subject to drying stresses. Consequently, the collector strip and inner edge of the AF-42 bond film was moved outward to reduce the additive stress condition.

Drawing 1076527-751 (Appendix) is the configuration of the SPE-electrode assembly used in B/U 4 and 5. The anode catalyst loading, which on earlier units had been lowered to 4 mg/cm² as a cost reduction, was again increased to 30 mg/cm² on B/U 4 and 5.

Oxygen System Configuration

In order to increase saturation of the oxygen entering the O₂ system compartments, the inlet configuration was modified as follows:

- 1) Increased length of O₂ inlet tube so that gas would be introduced at a point of greater water content in the product water wick.
- 2) Placed the O₂ inlet tube behind the product water wick.
- 3) Added a second layer of wicking in the O₂ inlet region.

The configuration of the O₂ frame, wick and screen assembly is shown in Dwg. 1076527-754. The wick assembly is shown in Dwg. 1076527-842 (see Appendix).

Stack Assembly Design

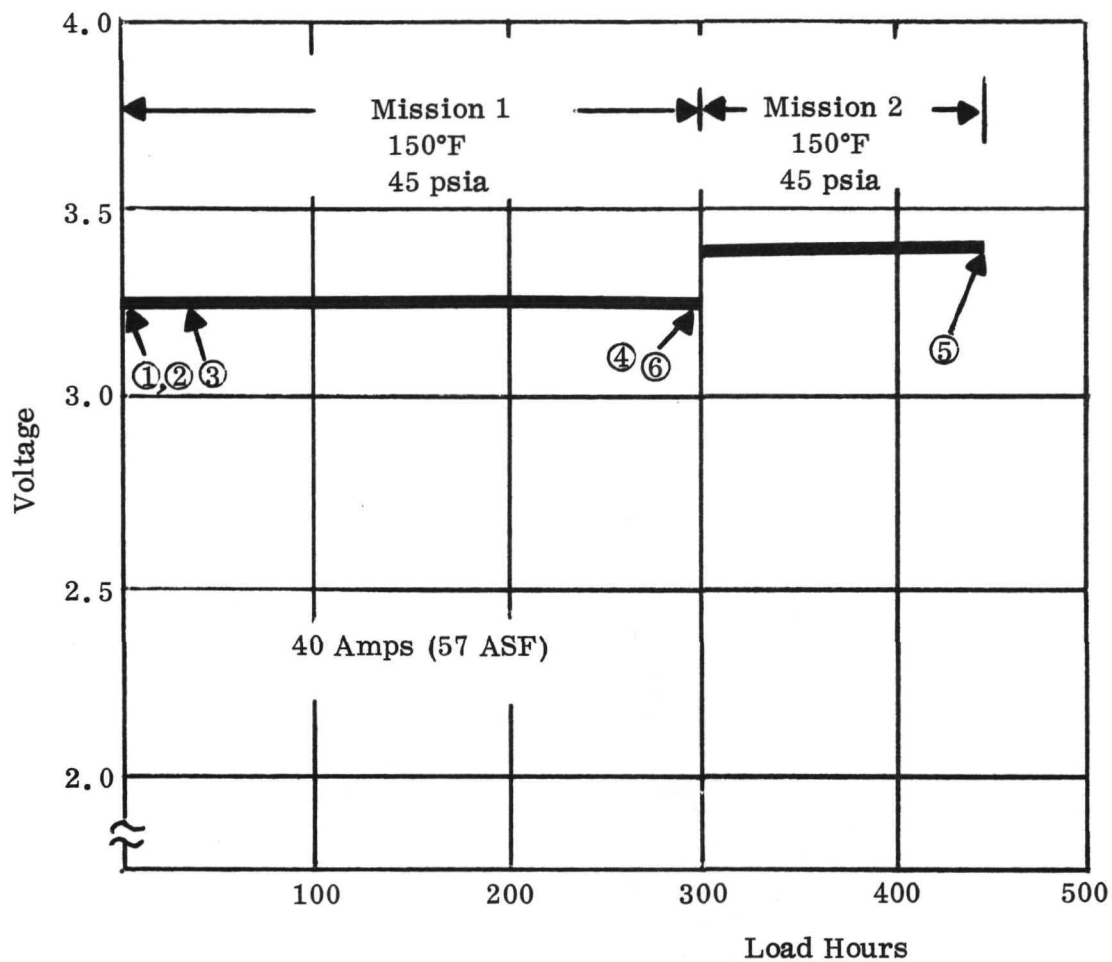
The configuration of the stack assembly, which was similar to B/U 2, incorporated the stack components designed for the EM-1 stack (light-weight end plates and simplified electrical connections). Two modifications introduced in B/U 4 were:

- 1) Addition of a second H₂ inlet port for the top H₂ channel.
- 2) Relocation of the water separator to the bottom of the stack to assure more uniform wick water content and prevent back-flow of separator contaminants to the SPE.

Test Performance

The performance level of B/U 4 was somewhat higher than B/U 1 and 2.

B/U 4 was tested satisfactorily until failure at 448 hours. Failure was caused by through-SPE leakage at the oxygen inlet. Performance is shown on Figures 29 and 30. The test report covering B/U 4 and 5 is summarized in GE document SPR-042.



- ① Deep Discharge
- ② Electrolysis
- ③ Coolant System Shutdown (14 hrs)
- ④ O₂ Takeover with Vacuum Purge and Vacuum Startup
- ⑤ Test Termination Due to Failure
- ⑥ Switch to LOX

Configuration:
 Compartmentalized H₂ Cavity
 High Water Content SPE
 Modified O₂ Inlet

Figure 29. Buildup 4 Performance (8 Cells)

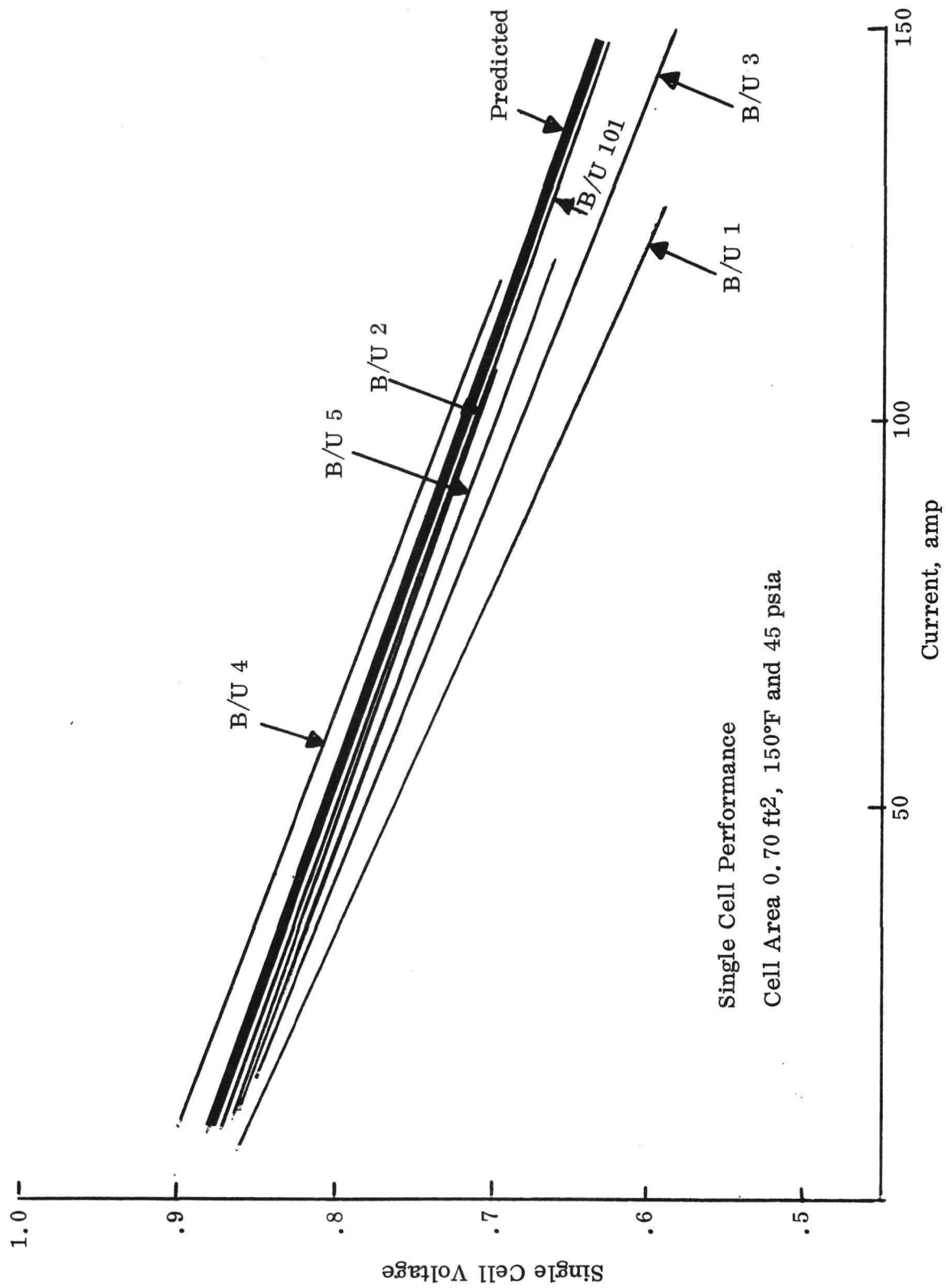


Figure 30. Single Cell Performance Comparisons

3.8.5

Buildup No. 5

Buildup No. 5 was funded by General Electric. It was fabricated with 8 cells and ready for test at the time of the failure of B/U 4. After review of the B/U 4 failure mechanism at the O₂ inlet, it was decided to prehumidify the oxygen during B/U 5 testing.

B/U 5 operated with saturated oxygen for 666 hours to failure. Performance was the same as B/U 1 and 2. The cause of failure was cross-SPE leakage at the H₂ inlets. See Figure 31.

The teardown of B/U 3 at about this time uncovered a gold-to-SPE bond leakage. B/U 5 was then rebuilt as B/U 5A with two original and two new cell assemblies. All the cells were potted in the gold-to-SPE bond area to prevent leakage. This unit operated for an additional 180 hours until failure occurred in one of the original cells. This failure was exactly like the one in B/U 5. Neither B/U 5 nor B/U 5A showed any oxygen inlet area SPE degradation.



Configuration: Same as Buildup 4
Pre-Humidified Oxygen

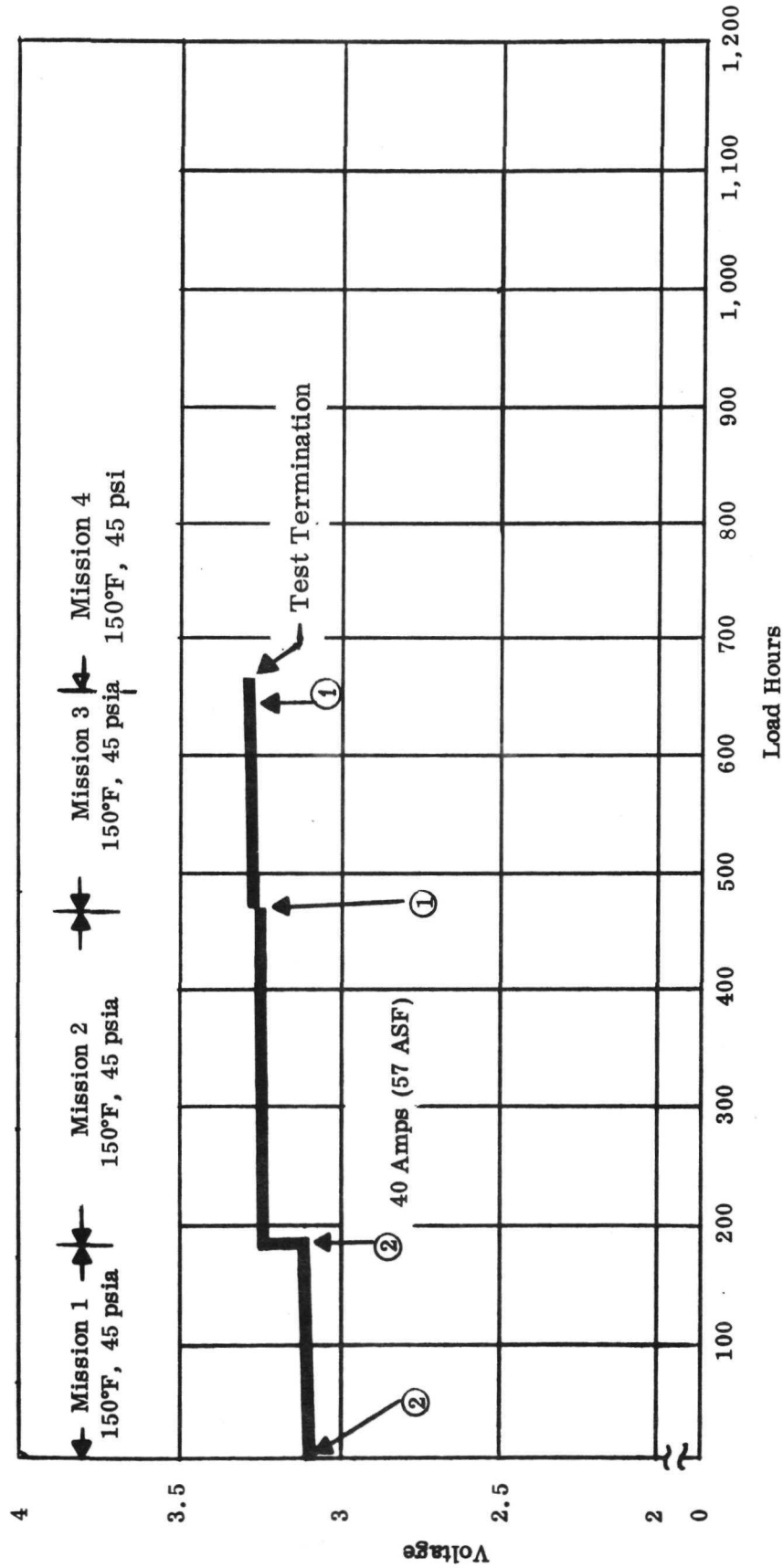


Figure 31. Buildup 5 Performance (8 Cells)

① Electrolysis

② O₂ Takeover with vacuum purge and electrical startup

The failures of B/U 4, 5 and 5A demonstrated that the Space Shuttle cell assembly design still had reactant inlet deficiencies which were not corrected by the design modifications introduced into these units.

The cause of the high rate of hydrogen fluoride release, the SPE reactant inlet delamination, and final stress cracking at reactant inlets was not understood. At first it was postulated that the cause was related to heat release due to bond leakage allowing O₂ and H₂ mixing and reacting on the anode catalyst at the inlet area and/or to the heat released during activation and discharge. B/U 5 and 5A testing, however, did not support these original postulates. In addition, laboratory test on 3 x 3 inch cells and bench testing on the SPE material could not reproduce the buildup failure observations by simulating the postulated conditions.

While the Space Shuttle fuel cell endurance failures were being encountered, two advanced ground power fuel cell buildups had been assembled and were undergoing endurance testing. The cells of the 4-cell buildup (AFC 6) were of the same active area and basic configuration as the Space Shuttle design. See Figure 32. This unit had, however, operated for 3000 hours at Space Shuttle load and temperature conditions without releasing hydrogen fluoride quantities in the product water above the limit of detection (approximately 1 ppm). This buildup had not, however, been exposed to the Space Shuttle multiple stop/start conditions.

AFC 6 was temporarily utilized in support of the Space Shuttle failure analysis. Stop/start procedures of the type used on Space Shuttle buildups were conducted on AFC 6. Product water analyses showed no indication of increased hydrogen fluoride. Subsequent to the stop/start testing, the buildup has, as of this writing, accumulated an additional 2000 hours (5000 hours total) at twice the Space Shuttle current densities and at 180°F coolant inlet temperature (max. cathode temperature 200°F).

The other test unit of the same boilerplate construction is a single cell unit (AFC 1) and which had been on a standby test at a trickle load of 1 ASF for more than 9000 hours at 150°F. Figure 33 shows the AFC 1 test setup.

The AFC 6 experience became the final proof that the stop/start procedures did not significantly affect fuel cell life.

A thorough analysis of the differences in design between the Space Shuttle units and AFC 6 was conducted. The major difference detected that could explain all the manifestations of SPE degradation and failure was that a high degree of reactant prehumidification was inherent in the AFC 6 cell design. In contrast, Space Shuttle units had virtually no prehumidification of the hydrogen reactant and only partial humidification of the oxygen reactant, with the exception of B/U 5 and 5A which had completely prehumidified oxygen.

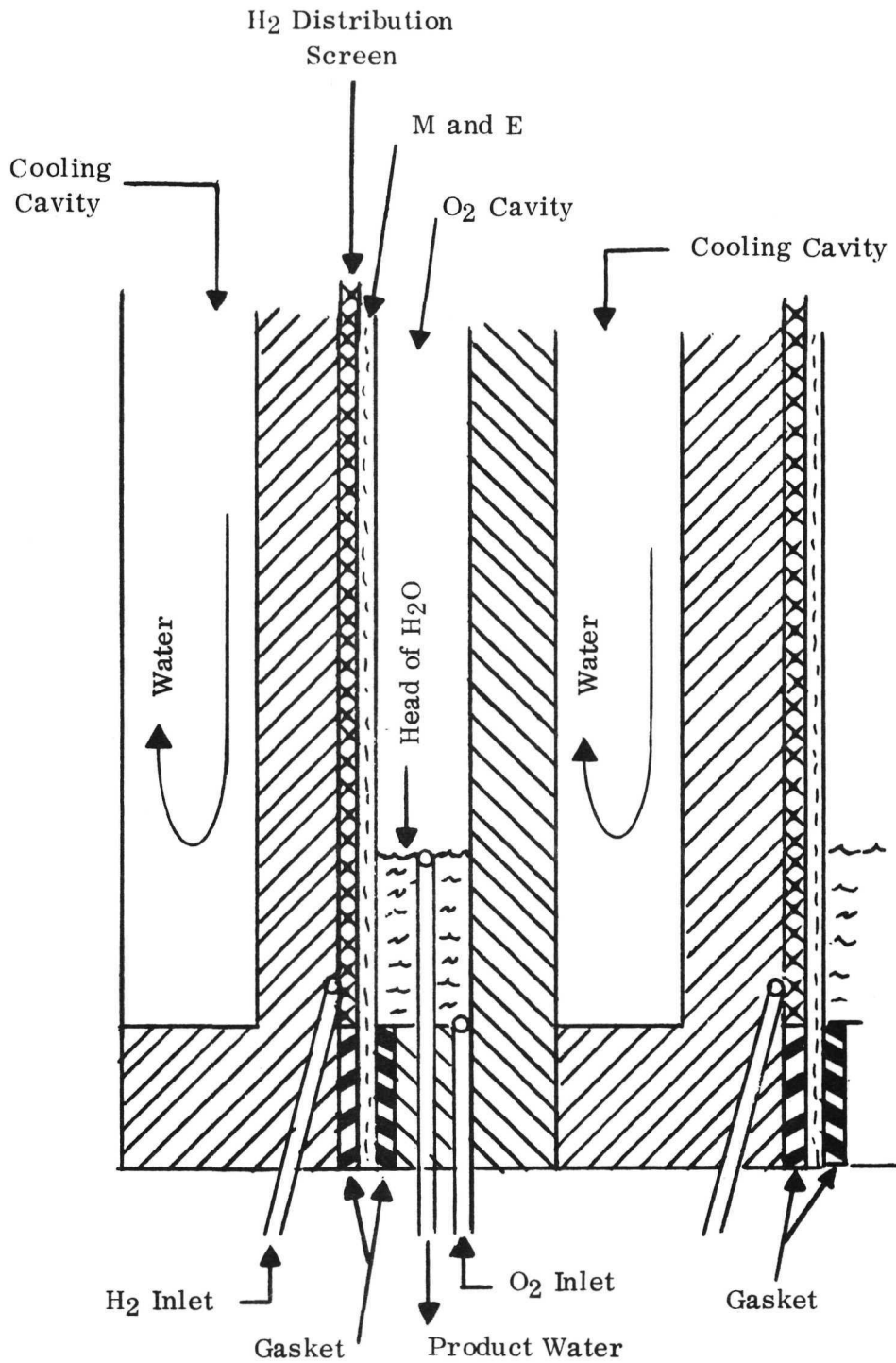


Figure 32. Advanced Fuel Cell Assembly Cross-Section

ADVANCED FUEL CELL

B U 1A

ACCELERATED STANDBY TEST
&
MISSION LIFE

TOTAL HOURS 7200

6 30 71

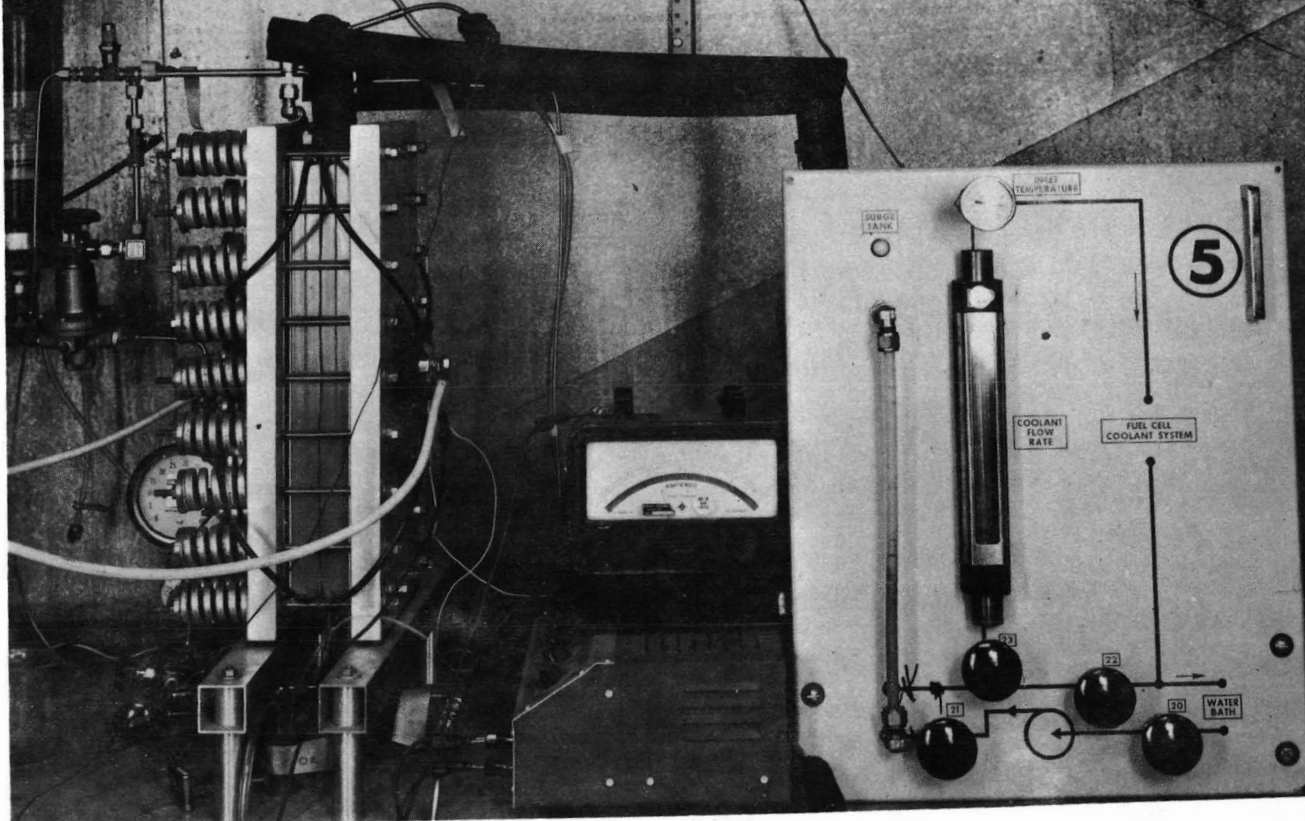


Figure 33. Advanced Fuel Cell (AFC 1) Test Setup

A matrix of 3 x 3 inch laboratory fuel cell tests was conducted to verify the effect of reactant humidification and other parameters relating to SPE degradation and delamination. In all the 39 cells tested, gasketed laboratory 3 x 3 inch hardware was used, with a cell active area of 7.2 in.² (1/20 ft²). The base line accelerated test condition was selected as:

- 1) SPE-electrode assembly of Buildup 4 configuration.
- 2) Point impingement of hydrogen gas achieved by blocking the hydrogen manifold with silicone rubber. This was to assure a worst case inlet drying condition.
- 3) 220°F operation.
- 4) 48 psig O₂/43 psig H₂.
- 5) Startup by electrical charging.
- 6) 100 ASF current density.
- 7) Dry gas feed.

The following parameters were selected for the initial evaluation:

Platinized vs. non-platinized SPE.
Extruded vs. skived SPE.
Wet vs. dry H₂.
Wet vs. dry O₂.
Temperature.
Pressure.
Activation techniques.
SPE water content.
Localized H₂ flow rate.
Cathode activity.
Cathode and anode catalyst loadings.

The above parameters were varied throughout the matrix testing. As a result of the testing, two significant conclusions were reached:

- 1) Humidification of hydrogen is the major parameter affecting SPE degradation. Humidified hydrogen prevented delamination and greatly reduced HF release. On an arbitrary rating scale of "Good", "Fair" and "Bad" based on HF release rate and degree of delamination, none of the cells that employed hydrogen humidification regardless of the level of other parameters received a "Bad" rating.

- 2) Removal of cathode catalyst in the areas of SPE ordinarily dried by impingement of dry reactants greatly reduced degradation.

Other conclusions from this testing are:

- 1) Non-platinized SPE is superior to platinized.
- 2) Extruded SPE is comparable to skived.
- 3) Increased temperatures increase rate of degradation.
- 4) Degradation increases slightly as pressure is decreased.
- 5) Activation technique has little effect on degradation.
- 6) SPE water content in the range from 28 to 40% has no significant effect on degradation.
- 7) Reactant flow rate has a second order effect on degradation.
- 8) Cathode activity has little effect on degradation.
- 9) Catalyst loading (anode or cathode) has no significant effect on degradation.

A detailed account of the matrix testing is given in GE document SPR-049, "Failure Analysis Summary Report".

The single cell and small stack test experiences of this program have clarified the primary failure mode of the solid polymer electrolyte. This failure mode is not random in nature, but is reactant inlet oriented.

3.9 Engineering Model EM-1 Fabrication

The fabrication and test of Engineering Model EM-1 was not completed. This effort was terminated in order to devote available funding to analysis of small stack test failures. However, a complete set of ancillary components, a set of bread-board electronics, and module container assemblies were accumulated for the Engineering Model.

4. TASK II - TECHNOLOGY ADVANCEMENT AND EXPLOITATION

A portion of this program was devoted to advancing the state-of-the-art in fuel cell related technologies.

4.1 Electrolyte Development

The first area concerned continuing electrolyte development. The original concept was to identify the optimum ion exchange capacity (IEC) of the solid polymer electrolyte as related to performance and life. However, it was determined that obtaining various IEC's of solid polymer electrolyte required a long lead time and would be quite expensive. This task was thus modified to evaluate various water contents of the proposed IEC of 0.8 milliequivalents per gram.

Optimum performance for SPE fuel cells was obtained with SPE's in which the water content has been adjusted to 36 - 42 wt %. The performance dividend of cells with SPE water contents in this range amounted to about 70 mv over similar cells with an SPE water content of 26 - 28 wt % at operational conditions of 180°F and 400 ASF in 1/20 ft² size cells. This performance improvement was not as apparent at low as it was at high current densities.

The life capability of an SPE cell containing 36 - 42 wt % water was five times that of a 26 - 28 wt % water content SPE which was the previous standard. Thus, a 36 - 42 wt % water content SPE cell operated at 180°F and 400 ASF would have an estimated life expectancy of 15,000 hours.

The life extension obtained with the higher water content SPE's corroborated earlier computer models of the water gradients present in operational SPE's, as well as the postulated failure mechanism of SPE fuel cells.

Physical and operational characteristics of increased water content SPE are displayed in Figures 34 thru 41.

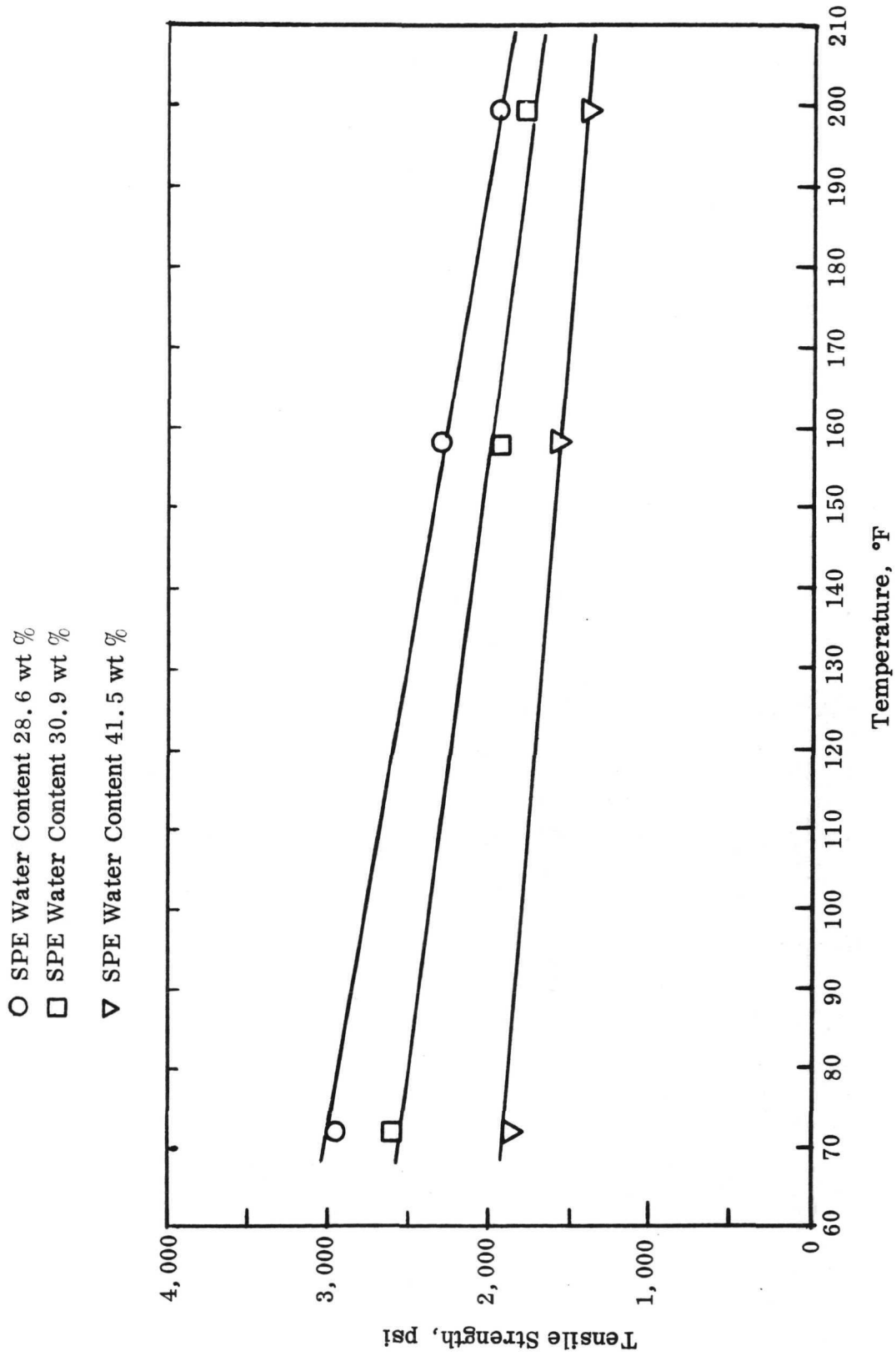


Figure 34. SPE Tensile Strength vs. Temperature

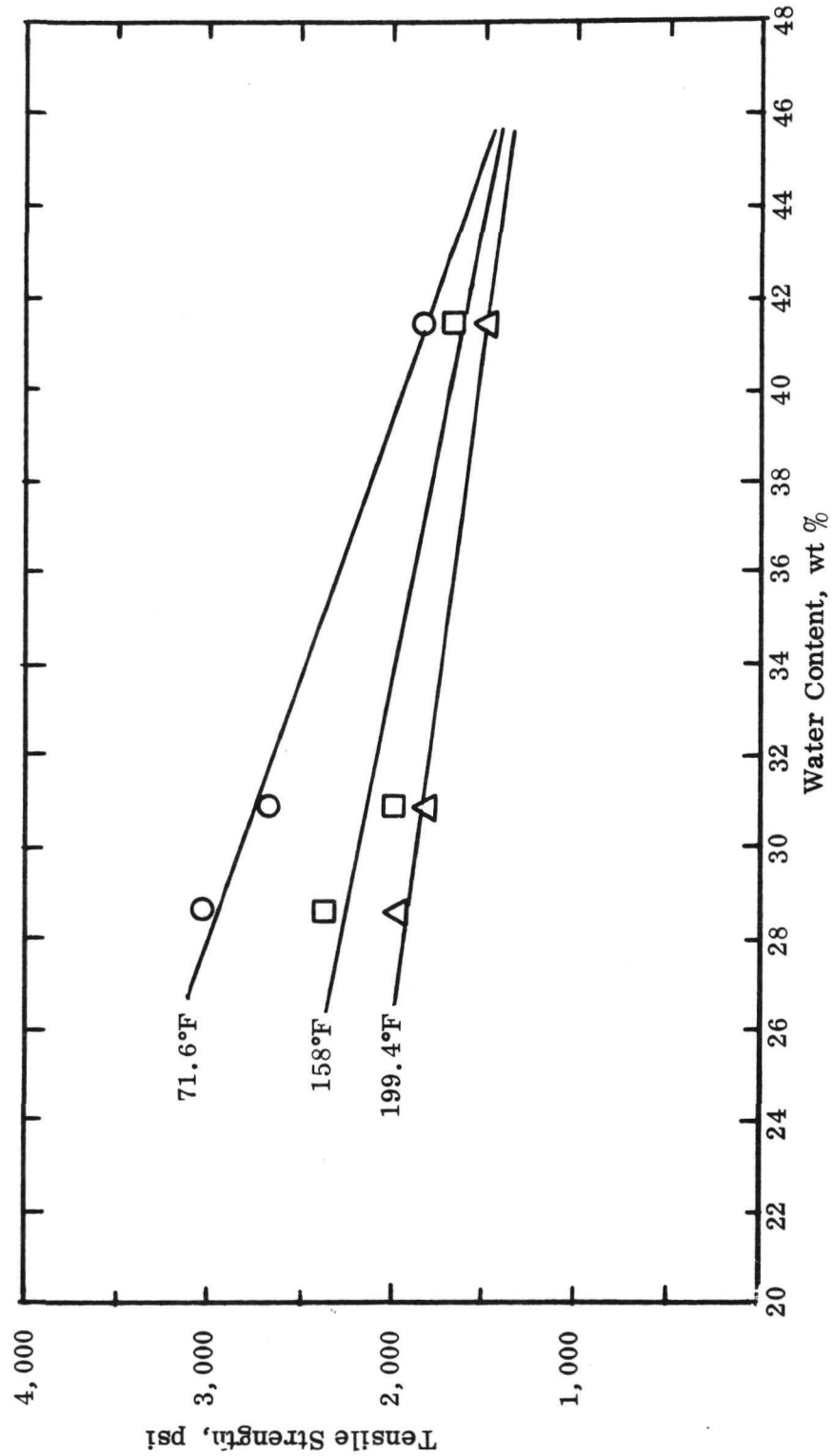


Figure 35. SPE Tensile Strength vs. Water Content

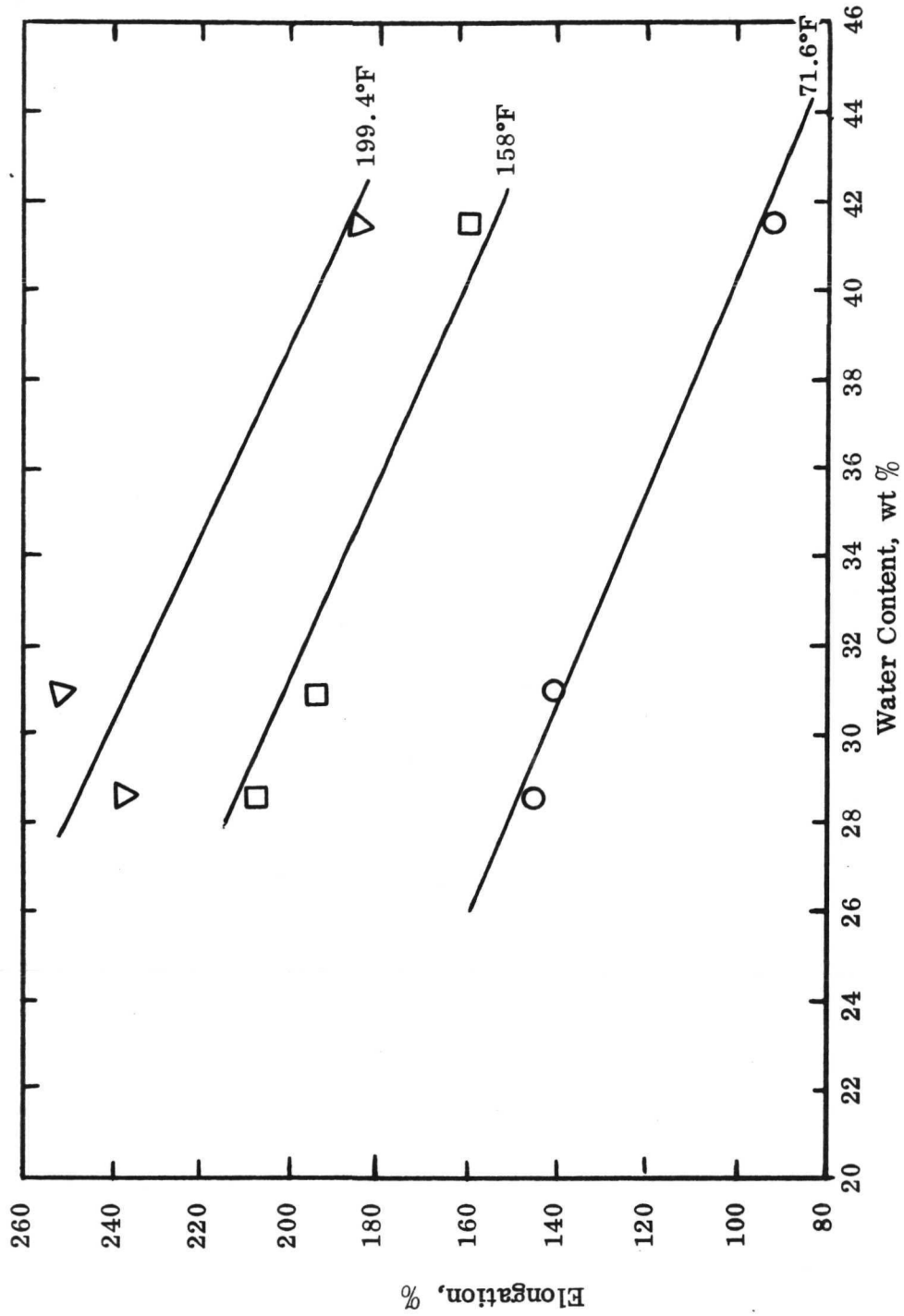


Figure 36. SPE Elongation vs. Water Content

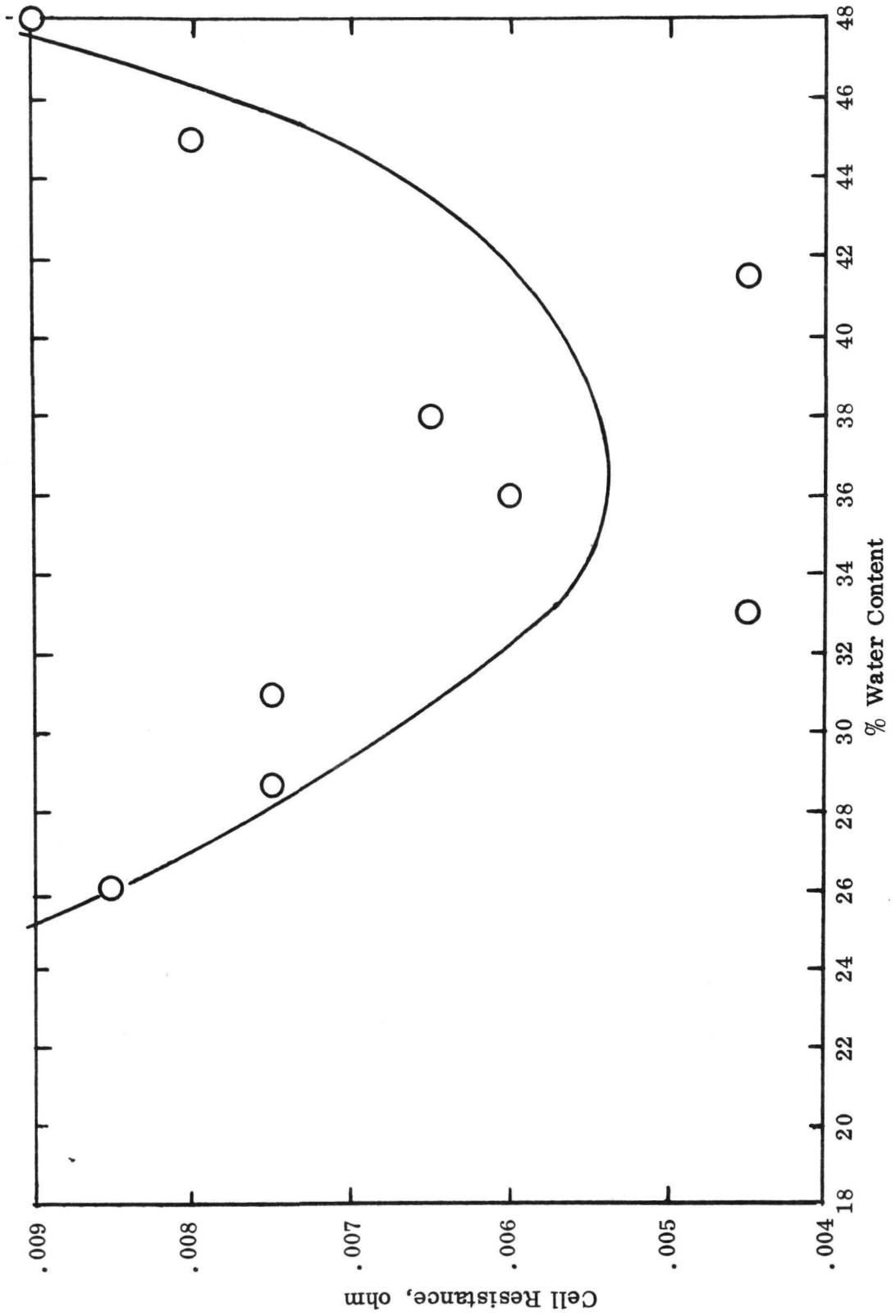


Figure 37. Cell Resistance vs. SPE Water Content - Cell Operation at 220°F, 500 ASF

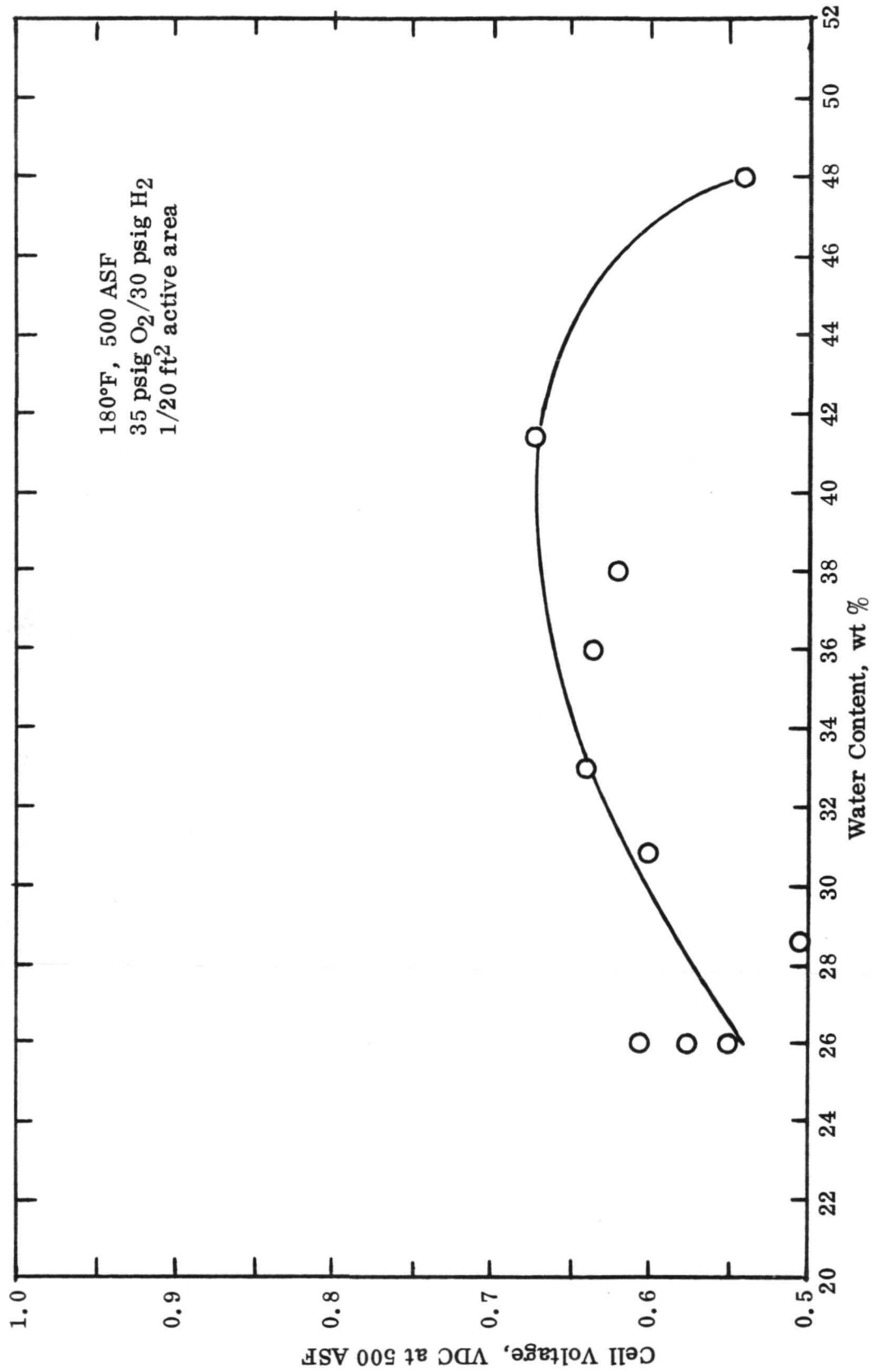


Figure 38. Cell Performance vs. Water Content

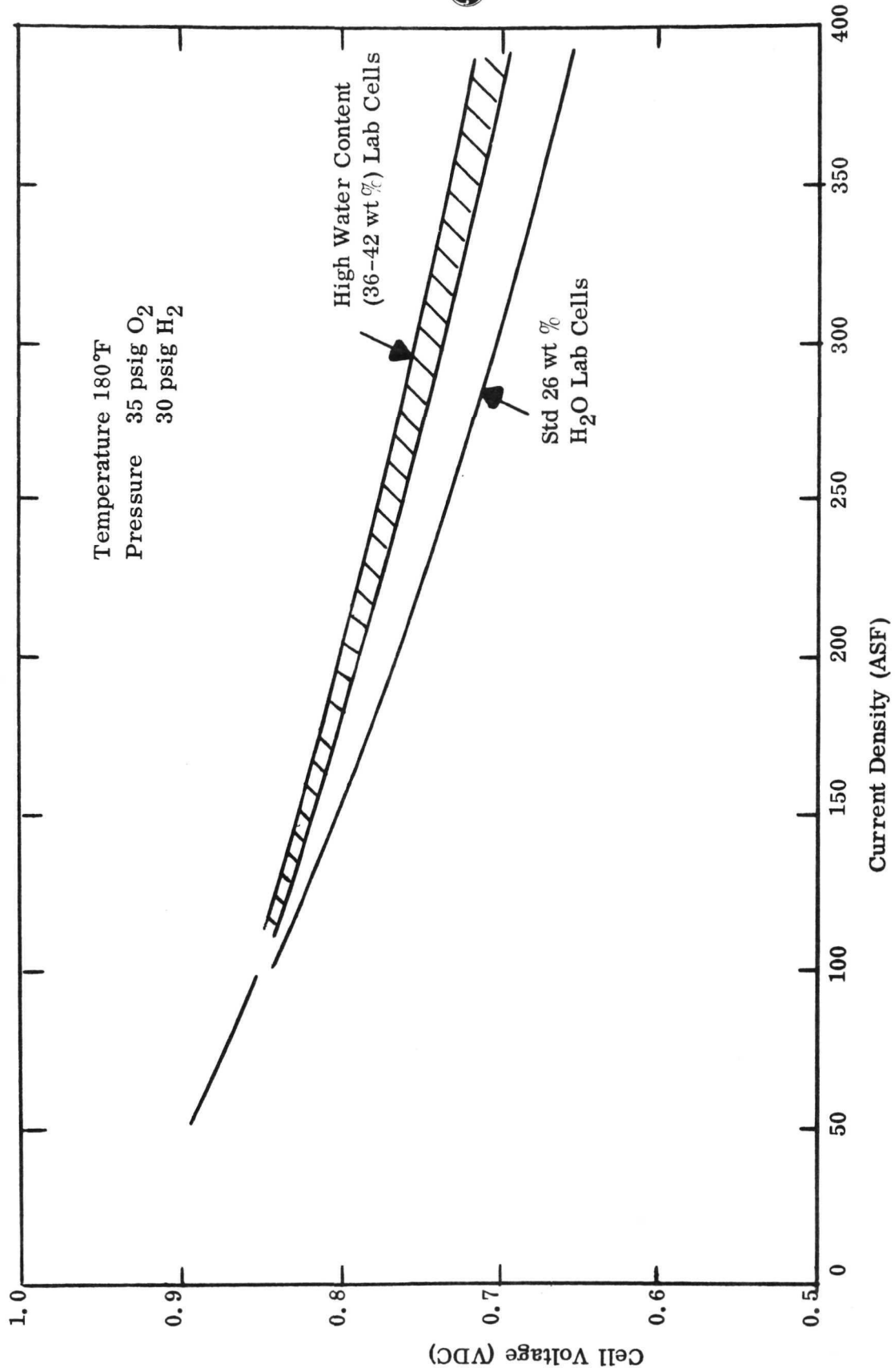


Figure 39. Performance of Standard and High Water Content SPE Cells

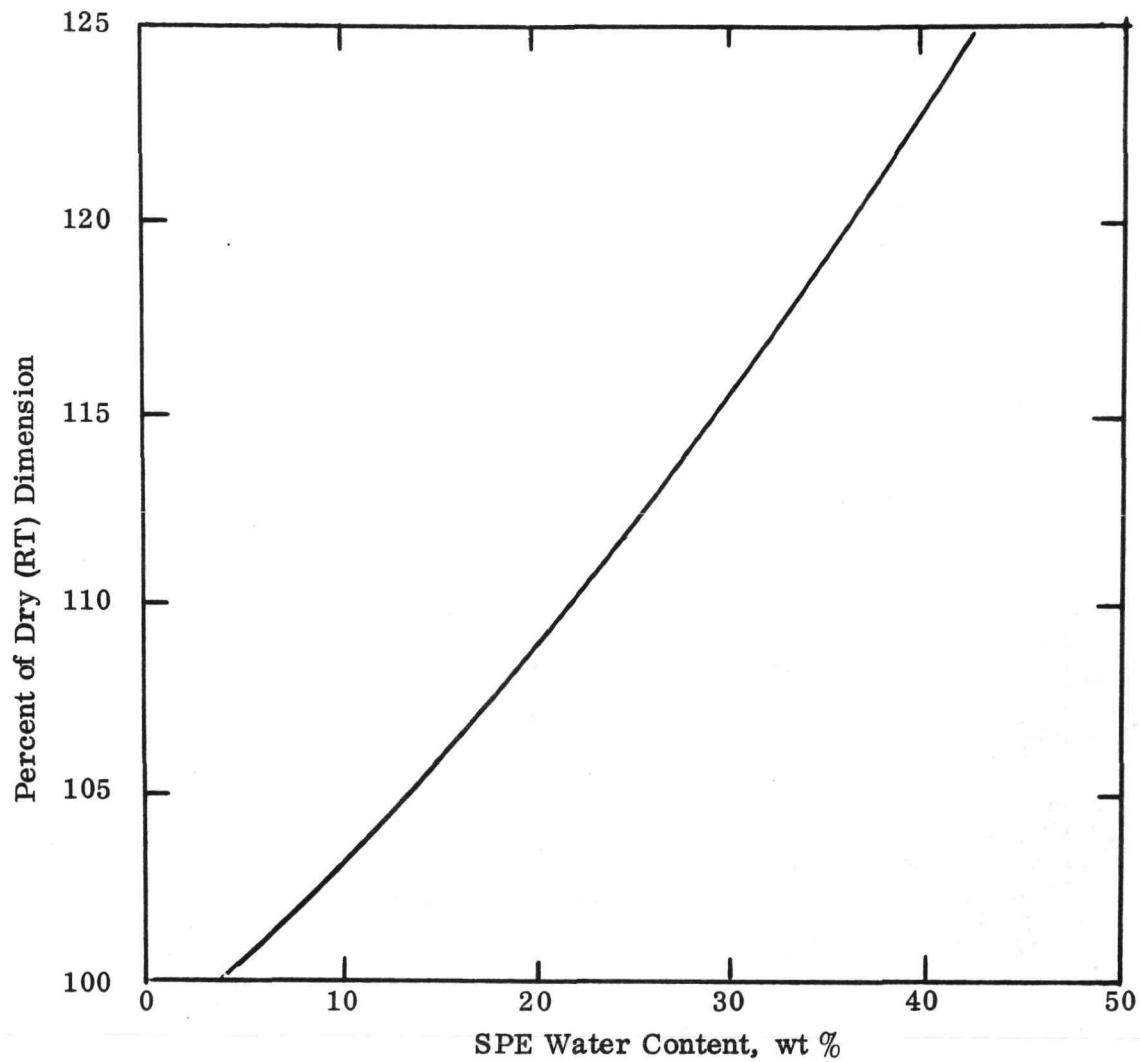


Figure 40. SPE Water Content vs. Dimension

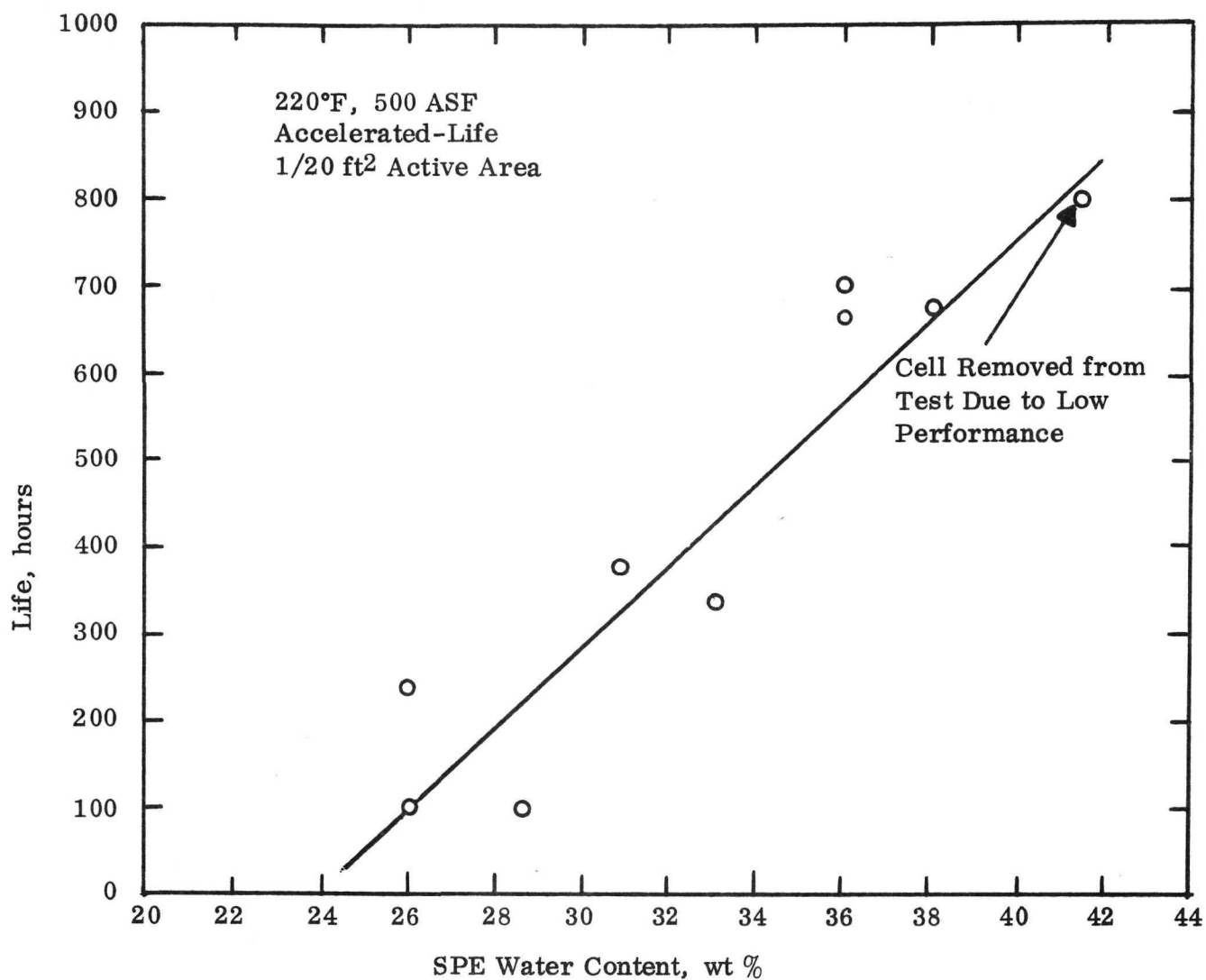


Figure 41. Accelerated Life Testing of Standard and High Water Content Cells

4.2 Ti-Pd as a Construction Material

A second portion of the technology advancement subtask was related to studies of the use of titanium-palladium as a fuel cell construction material. The weight saving by replacing niobium with Ti-Pd was considered significant but its compatibility in the fuel cell environment was questionable.

A corrosion study was conducted with titanium - 0.2 palladium (Ti-0.2 Pd) foil in the anode environment of advanced SPE fuel cells in laboratory-size (1/20 ft²) hardware. The purpose of the evaluation was to determine whether the Ti-0.2 Pd alloy could be safely substituted for niobium in the anode coolant cartridge structure, thus accomplishing a significant weight saving. It was found that the Ti-0.2 Pd alloy was seriously affected by hydrogen embrittlement in the anode environment of the advanced SPE fuel cell at 34 psig of hydrogen gas and 180°F. See Figure 42.

Efforts to protect the Ti-0.2 Pd alloy from hydrogen embrittlement by annealing and platinum plating proved only moderately successful. See Figure 43 and Table VI.

Table VI

Hydrogen Embrittlement Test Samples

Samples (A through F Ti-0.2 Pd .003 inch foil). See Figure 42.

A - Platinized, air annealed, H ₂ O quench	E - Vacuum annealed, platinized
B - Air annealed, H ₂ O quench	F - Platinized, vacuum annealed
C - Platinized, air annealed, air quench	G - Niobium foil, .003 inch
D - Air annealed, air quench	

The order of resistance to embrittlement after 609 hours at 180°F in the H₂ compartment at 150 ASF of an advanced SPE cell in laboratory size hardware (1/20 ft²) was: G >> E ≈ B ≈ D > A ≈ C ≈ F

Using the weight loss techniques, it was found that corrosion of the Ti-0.2 Pd alloy foil was equivalent to niobium foil in the SPE fuel cell environment at 180°F (Table VII). However, the fact that Ti-0.2 Pd alloy became so badly hydrogen embrittled has precluded its use as a substitute for niobium in this particular application.

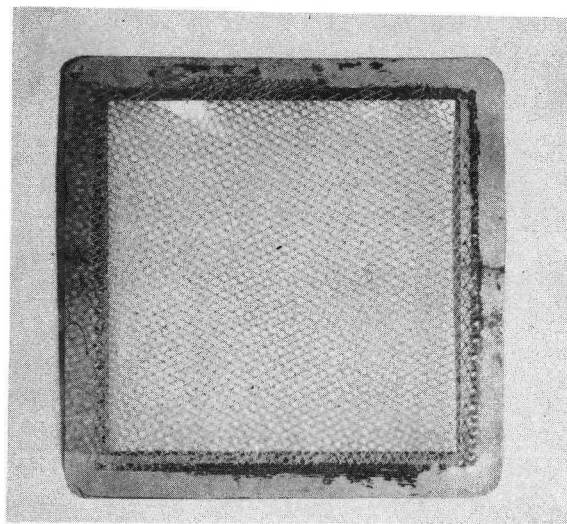
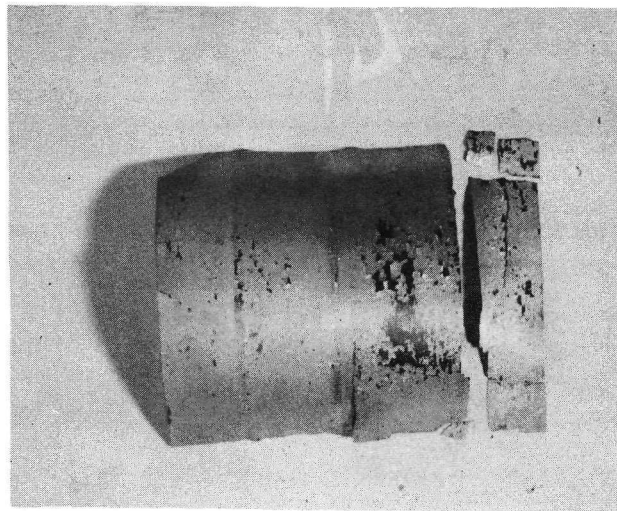


Figure 42. Platinized Ti-0.2 Pd Foil and Screen Samples After Test

Cell No. 87-L
M and E TMS-563
180°F
150 ASF

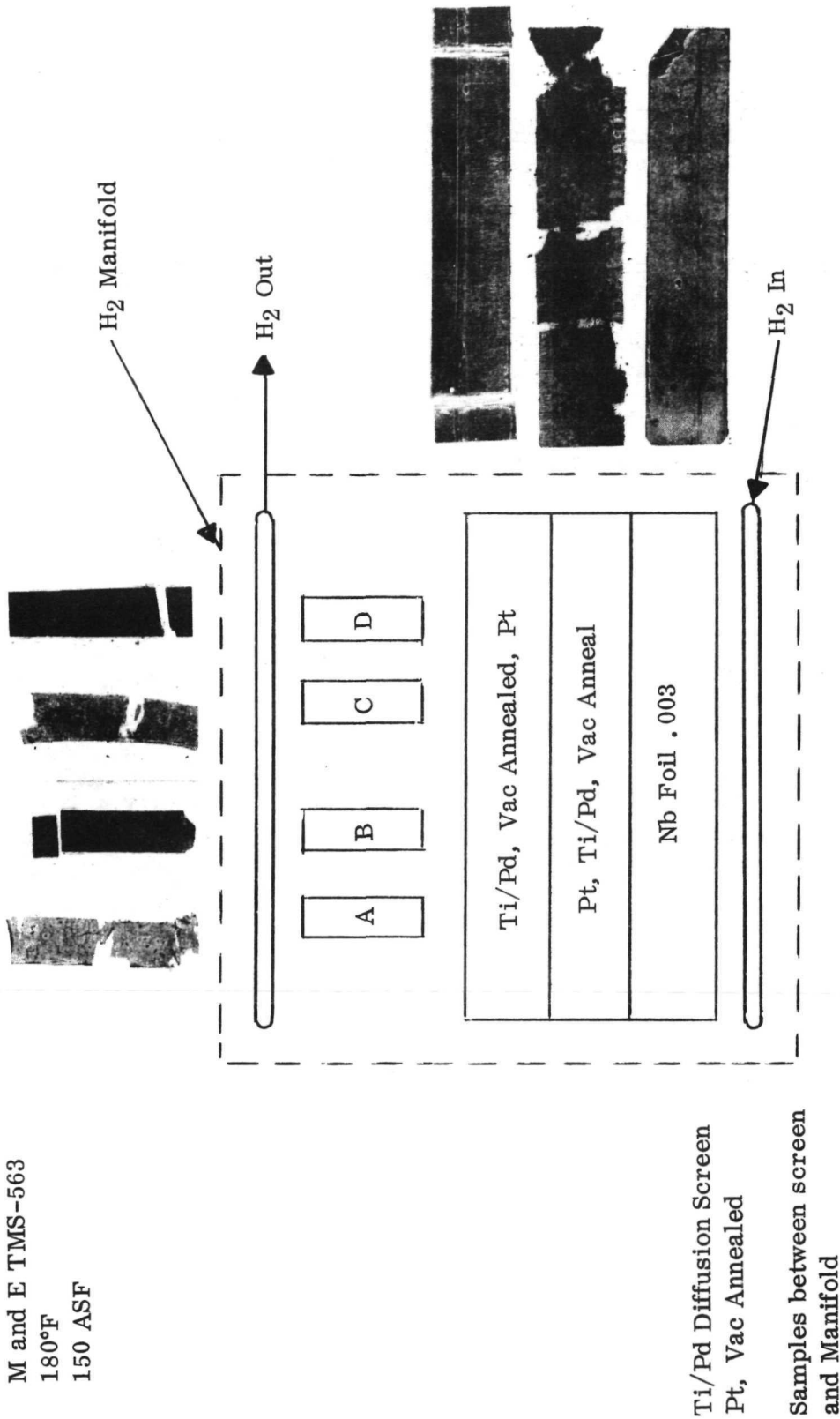


Figure 43. Hydrogen Embrittlement Test Setup

Table VII

Corrosion of Ti-0.2 Pd and Nb at Hydrogen Potentials
Samples Suspended in 12 ppm HF Solution at 180° F

<u>Sample Description</u>	<u>Corrosion Rate at 3200 hrs (mils/year) x 10⁻³</u>
1. Ti-Pd foil	11.9
2. Ti-0.2 Pd foil platinized 1.7 mg/cm ²	83
3. Ti-0.2 Pd expanded screen	35.7
4. Ti-0.2 Pd expanded screen platinized 1.6 mg/cm ²	357
5. Ti-0.2 Pd expanded screen platinized 0.8 mg/cm ²	374
6. Niobium foil	170
7. Niobium expanded screen	1390

NOTE: Fluoride in concentration was kept above 10 mg/liter.
Corrosion rates were calculated using weight loss data. Results
for Ti-0.2 Pd may be biased because of oxide buildup even at
hydrogen potentials.

4.3

Bonding System Evaluations

Another task was the evaluation of the proposed bonding systems in the various potential fuel cell environments. Previous evaluations were run in 180°F distilled water only.

Tests were conducted to evaluate the aging characteristics of primed/unprimed components bonded with 3M Company AF-42 adhesive and aged in water at 200°F. Additional aging tests were carried out with primed/unprimed samples in 40 wt % ethylene glycol/water solution and Coolanol 25. These conditions were to simulate bond environments in the SPE cell compartment and on the coolant cartridge.

Bond samples made with primed components withstood aging in the various liquids better than the unprimed samples. Water aging and Coolanol 25 aging had about the same effect on sample bonds, but aging in glycol solution was much more damaging to the bond peel strength. See Table VIII.

The advanced SPE cell was successfully bonded to polysulfone in the wet condition. That is, it was not necessary to dry the SPE and electrode assembly bond area edges prior to bonding to the polysulfone frame. This simplifies the bonding procedure by elimination of the preliminary oven drying step for the SPE and electrode assembly.

Instron peel tests of cell assemblies bonded by the new "wet bonded" procedure compared well with cell assemblies bonded with the previous "dry bonded" procedure.

Adhesive bond peel strengths of full-sized cell assemblies which had been operated at 150°F and 1000 and 2800 hours indicated that little or no bond deterioration had occurred. These modules had been "dry bonded" with no primer. A third cell assembly was evaluated for bond peel strength after 892 hours of operation at 150°F. This module had been manufactured using the new "wet bonded" technique. Again, little or no bond deterioration was detected.

Table VIII

Bond Peel Strength Data

	Primer with Davon 24, Primer Oven Cured, "R" Dried at 220°F. Membrane Primed.				Primer with Davon 24, Primer Air Dried, "R" Oven Dried at 125°F. Membrane Unprimed.				Davon 24 Primer. Air Dried.				Davon 24 Primer. Air Dried.			
	Water at 200°F		Water at 200°F		Water at 200°F		Water at 200°F		Coolanol at 200°F		Coolanol at 200°F		Coolanol at 200°F		40% Glycol at 200°F	
	Nb/PS	10PS/"R" 40PS/"R"	Nb/PS	10PS/"R" 40PS/"R"	Nb/PS	10PS/"R" 40PS/"R"	Nb/PS	10PS/"R" 40PS/"R"	Nb/PS	PS/PS	Nb/PS	PS/PS	Nb/PS	PS/PS	Nb/PS	PS/PS
Initial Peel (lb/in.)	18	NT*	NT	NT	27	NT	NT	NT	17	NT	27.5	NT	15.5	NT	24	NT
After 100 Hours (lb/in.)	8.6	NT(2) 28(1)	NT	NT	17.3	NT(1) 27(2)	NT	NT	13	NT	22.6	NT	7.7	NT(1) 23.5(2)	16	NT
After 500 Hours (lb/in.)	11.7	NT	NT(2) 16(1)	NT	19.3	NT(2) 30(1)	NT	NT	14	NT	18	NT	9.3	NT(1) 13(2)	10.5	NT
After 1000 Hours (lb/in.)	11.3	NT	NT	NT	16.6	NT	NT	NT	8.6	NT	13.3	NT	5	0	7	3
After 2000 Hours (lb/in.)	5	0	0	0	4	0	0	0	5	NT	7.6	NT	0	0	0	0
After 5000 Hours (lb/in.)	4	0	0	0	4	0	0	0	2.5	NT	3	NT	0	0	0	0

*NT = Indicates bonded material tore or broke during the Instron test, while the bond itself remained intact.

4.4 Product Water Removal Subsystem Materials

Fuel cell product water removal subsystem materials were investigated to determine capabilities of proposed material and to evaluate potential alternative materials.

The water management system for the Space Shuttle SPE fuel cell design was found adequate to handle water production even at the peak power level of operation. The Dacron wick had a water flux capability to water production ratio of nearly 4 to 1 at peak power and a ratio of almost 9 to 1 at average power. Water flux through the porous glass tube separators showed a capability to water production ratio of close to 38 to 1, based on 13 separator tubes per stack, at peak power levels and more than 85 to 1 ratio at average power levels. See Figure 44.

A market search for porous material to replace the porous glass separators was instituted because of concern over the possibility of long-term corrosion caused by small amounts of hydrofluoric acid in the product water. However, no material was found to adequately replace the glass tube separators. See Table IX.

A corrosion study showed that porous glass water separator tubes were quite adequate for the Space Shuttle water management system. Samples immersed in 5 and 10 ppm HF showed no change in bubble point after 2257 hours at 180°F. The weight losses of the samples in these solutions was only 1.3 and 3.2%, respectively. A sample immersed in 50 ppm HF solution for 2257 hours lost 11% of its initial weight, became quite chalky to the touch and underwent a drop in bubble point from 5-6.5 down to 2.5 psid. See Table X.

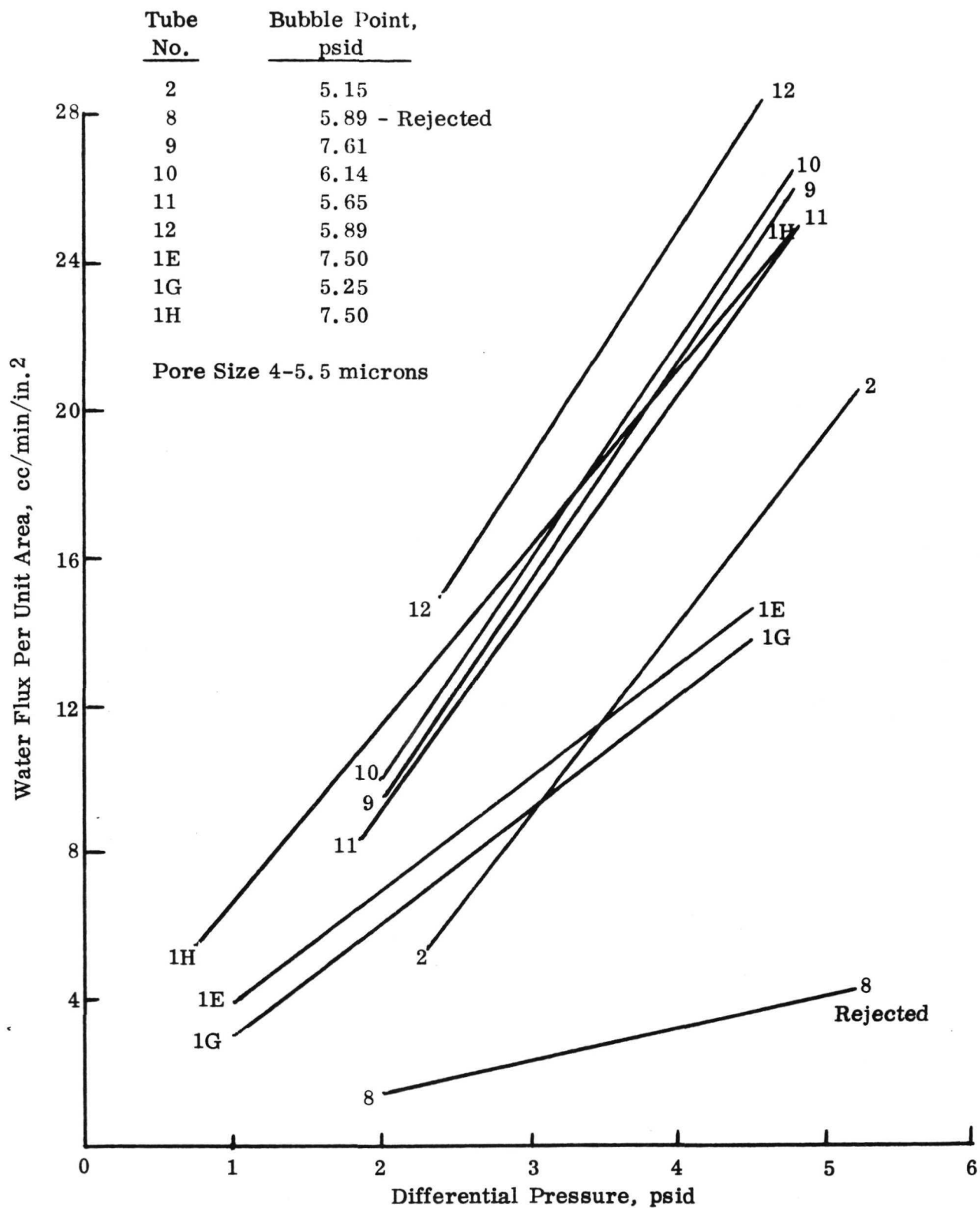


Figure 44. Porous Glass Separator Flux vs. Differential Pressure

Table IX

Materials Evaluated as Substitutes for Porous Glass Water Separator

<u>Chemplast Porous Teflon</u>		<u>Bubble Point, psid</u>
E610-122	5-10 micron pore size hydrophobic	< 1
E610-222	2-5 micron pore size hydrophobic	< 1
E610-222/2	2-5 micron pore size wettable	1
<u>Shamban Unsintered Porous Teflon</u>		
220011	pore size unknown hydrophobic	< 1
<u>GE Porous Polycarbonate</u>		
GE 300	3 micron pore size wettable	2-3
GE 100	1 micron pore size wettable	< 1
<u>Borg Warner Porous ABS Tube</u>		
Micro-Por	pore size unknown wettable	1
<u>*Corning Porous Glass Tubes</u>		
Very fine	2-2.5 micron pore size wettable	12-15
Fine	4-5.5 micron pore size wettable	6-7

*Included for comparison.



Table X

Porous Glass Water Separator Corrosion Test at 180°F

Initial Porous Glass Tube Wgt., g	168 hrs		335 hrs		502 hrs		700 hrs		935 hrs		1173 hrs		1463 hrs		2024 hrs		2237 hrs		Cumulative wt loss, g
	wt loss, g	% loss	wt loss, g	% loss	wt loss, g	% loss	wt loss, g	% loss	wt loss, g	% loss	wt loss, g	% loss	wt loss, g	% loss	wt loss, g	% loss	wt loss, g	% loss	
5 ppm HF 23.0010	0.0163	0.07	0.0018	0.008	0.0239	0.104	0.020	0.0087	0.0155	0.053	0.0445	0.194	0.0943	0.412	0.0273	0.12	0.0692	0.33	1.3
10 ppm HF 21.1951	0.0219	0.103	0.0310	0.146	0.0512	0.24	0.055	0.26	0.0815	0.39	0.0850	0.406	0.1775	0.852	0.0642	0.31	0.0993	0.48	2.2
50 ppm HF 18.0650	0.1627	0.9	0.1690	0.94	0.1968	1.1	0.1970	1.12	0.207	1.19	0.1988	1.16	0.3192	1.88	0.1988	1.19	0.2419	1.47	11
Bubble Point, psid																			
5 ppm HF 5.5-6.5	6-8		5.5-6.5	6-6.5	6-6.5	6-6.5	6.5-7	6.5-7	6.5-7	6.5-7	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	
10 ppm HF 5-6	6-8		5.5-6.0	6-6.5	6-6.5	6-6.5	6-6.5	6-6.5	6-6.5	6-6.5	6	6	6	6	6.0	6.0	6.0	6.0	
50 ppm HF 5-6.5	5-7		4.5-6.5	3 psi	heavy leak	3 psi	3	3	3	3	3	3	3	3	2.5	2.5	2.5	2.5	



Reactant Humidification

The failure analyses of the fuel cell buildups revealed the desirability of maintaining SPE moisture at the reactant inlets to minimize solid polymer electrolyte degradation. Humidification of dry hydrogen and oxygen was demonstrated by using an SPE without catalyst to transport product water into the reactant stream, thus humidifying the reactant at the coolant temperature. See Figures 45 thru 47.

The efficiency of the device decreased with increased reactant flow. Figure 48 shows this condition. A life test of more than 800 hours showed essentially no efficiency loss for both hydrogen and oxygen reactants.

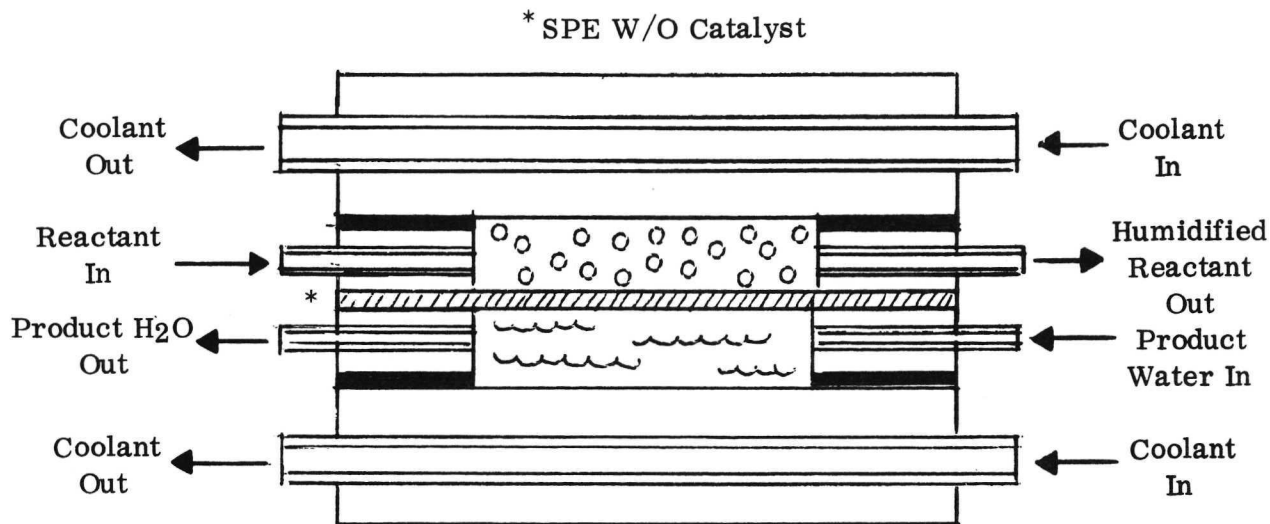


Figure 45. Flight-Type Reactant Humidification Demonstrator

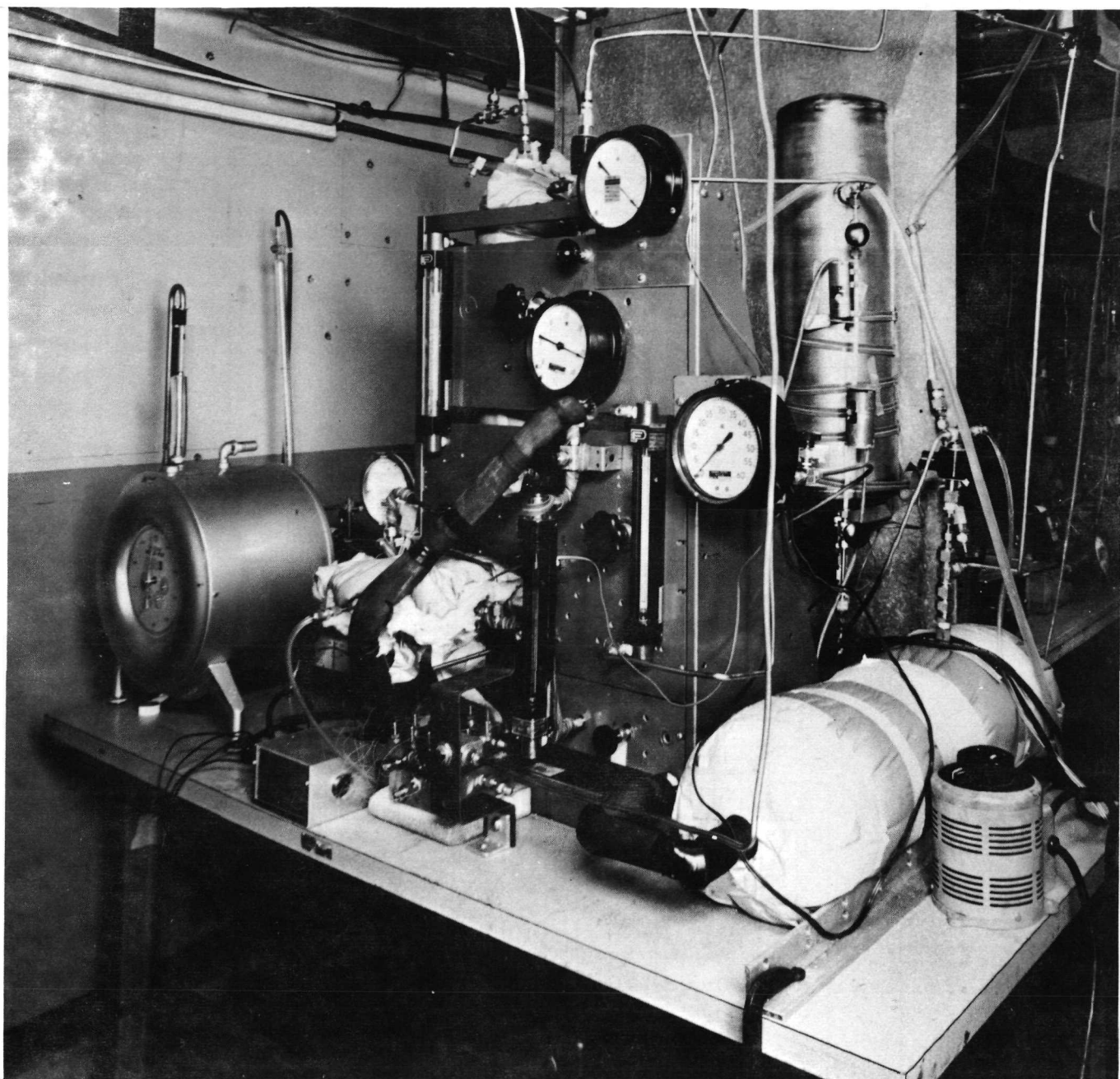


Figure 46. H₂ and O₂ Humidification Test Setup

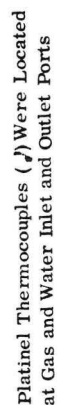


Figure 47. Gas Humidification Test Fluid Schematic

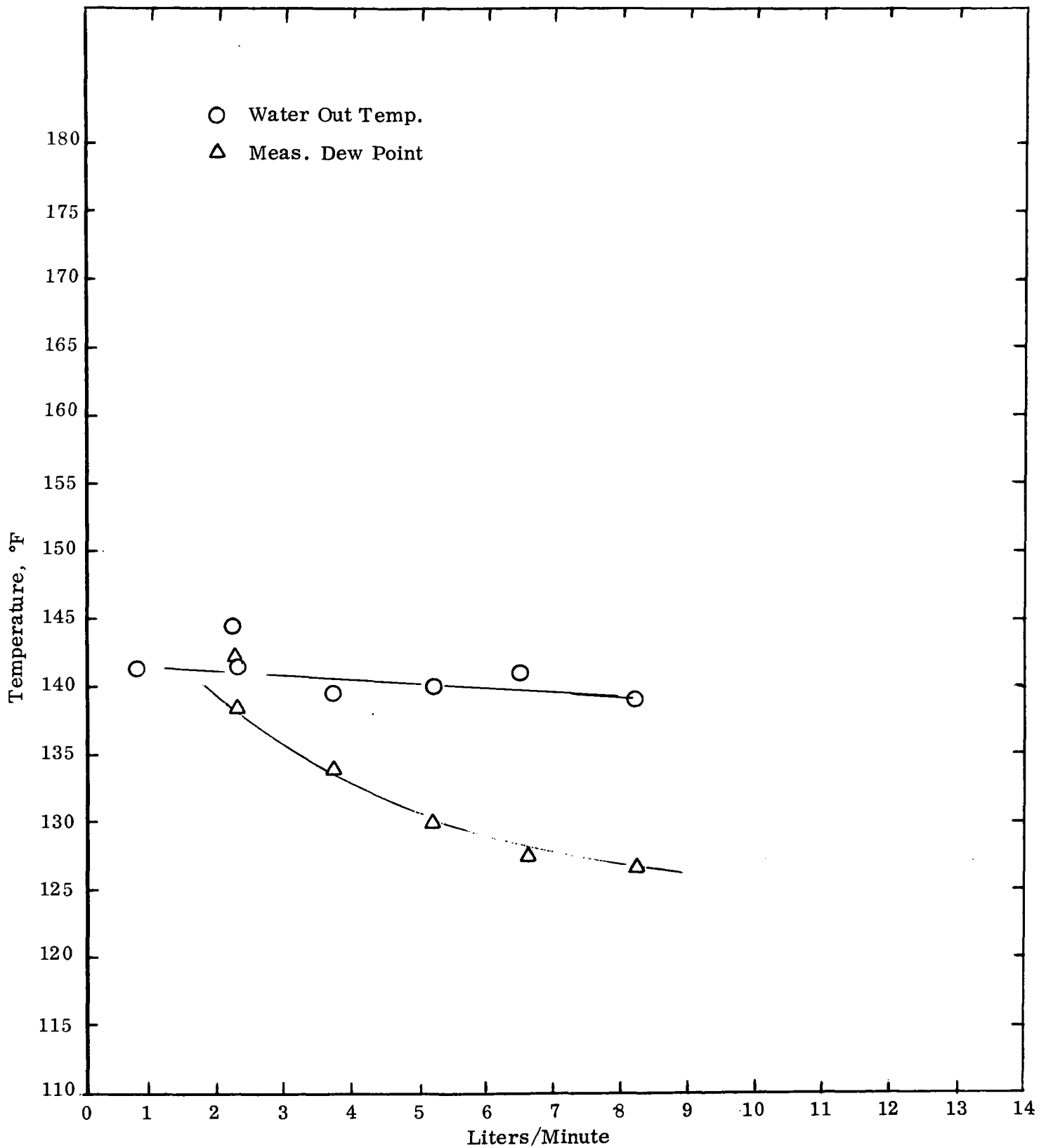


Figure 48. 3 x 3 Inch Cell O₂ Prehumidification with 150°F Equilibrated Skived SPE

5. TASK III - PHASE B CONTRACTS ACTIVITIES

Liaison with Prime Contractors

The liaison effort between GE/DECP and the Space Shuttle prime contractors resulted in the exchange of quantities of engineering data. Figures 49 thru 53 and Tables XI thru XIV give results of study efforts presented by GE/DECP.

Table XI

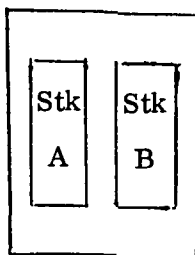
PACKAGING TRADE-OFF STUDY

Cryogenic Supply Pressures (100 to 1000 psia)

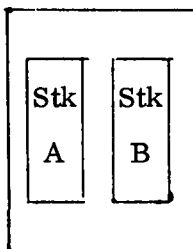
Base Line Fuel Cell Power Supply

- . Operation at 50 psia and 180°F
- . Rated output of 5 KW per module
- . Requires two stacks of 34 cells
- . Inherent voltage regulation $\pm 11\%$ (0 to rated)
- . Two stacks (5 KW) is emergency or fail-safe power level for 24 hours
- . Normal vehicle power load of 5 KW average and 10 KW peaks to be carried on two FCP's or four stacks

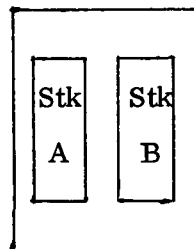
Base Line Configuration



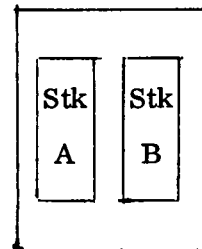
FCP #1
(Emergency)



FCP #2
(Fail-Safe)



FCP #3
(Fail-Op.)



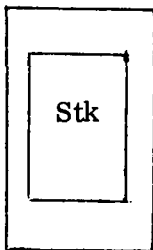
FCP #4
(Fail-Op.)

Weight of a two stack - 34 cells/stack module	= 114 lbs
Load per stack all operating 5 KW/8	= .625 KW
Parasitic load per stack 100 watts/2	= .050 KW
Total	.675 KW

Specific reactant consumption - .786 lb/KW-hr
 Total mission power 200 hrs x .675 x 8 - 1080 KW-hrs
 Total reactant consumption .786 x 1080 - 850 lb
 Cryogenic tankage factor 0.40 x 850 - 340 lb
 Module reliability - .975963
 System reliability - mission - .999938
 fail-safe - .999993



Alternate Configuration



Stk

Stk

Stk

Stk

Stk

FCP #6

(Emergency)

(Fail-Safe)

(Fail-Op.)

(Fail-Op.)

= 66 lbs

$$= .835 \text{ KW}$$
$$= .100 \text{ KW}$$

.935 KW

fail-safe - .999208

<u>Summary</u>	<u>Total System Wt</u>	<u>Mission</u>	<u>Fail-Safe</u>	<u>Modules</u>
Base Line	1646 lb	.999938	.999993	4
Alternate	1656 lb	.999074	.999208	6

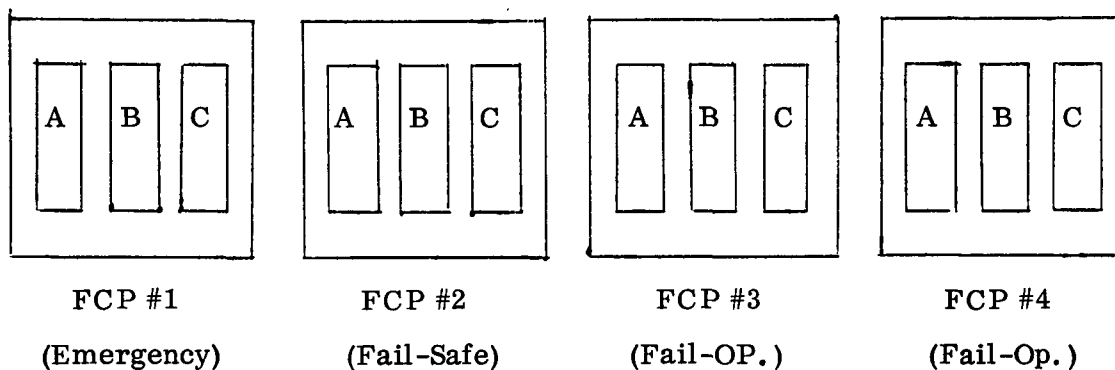
Cost effectiveness is a stand-off.

Propulsion Tank Pressures (20 to 45 psia)

Base Line Fuel Cell Power Supply

- . Operation at 20 psia and 150°F
- . Rated output of 5 KW per module
- . Inherent voltage regulation $\pm 12\%$ (0 to rated)
- . Requires three stacks of 35 cells
- . Three stacks (5 KW) is emergency or fail-safe power level for 24 hours
- . Normal vehicle power load of 5 KW average and 10 KW peaks to be carried on two FCP's or six stacks

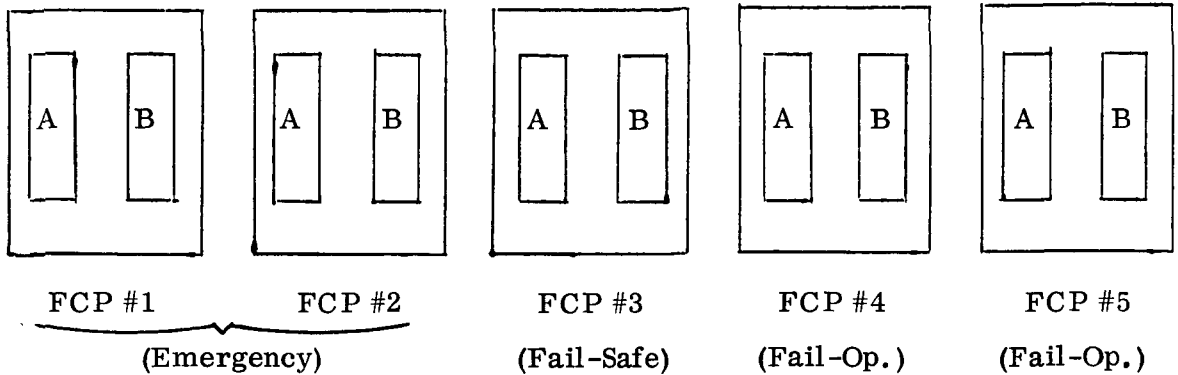
Base Line Configuration



Weight of a three stack - 35 cell/stack module	= 167 lb
Load per stack all operating 5 KW/8	= .416 KW
Parasitic load per stack 100 watts/3	= <u>.033 KW</u>
Total	.449 KW

Specific reactant consumption - .794 lb/KW-hr
 Total mission power 200 hrs x .449 x 12 - 1080 KW-hrs
 Total reactant consumption 1080 x .794 - 855 lb
 Cryogenic tankage factor 0.40 x 855 - 342 lb
 Module reliability - .970726
 System reliability - mission - .999893
 fail-safe - .999990

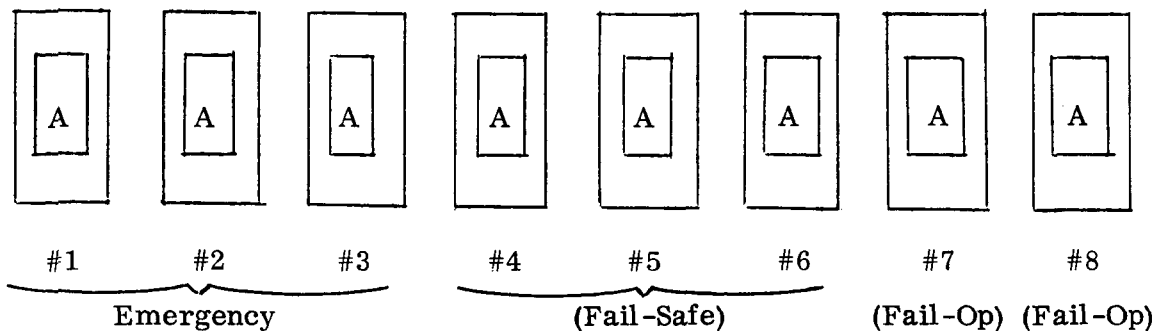
Alternate Configuration #1



Weight of a two stack - 35 cell/stack module	= 116 lb
Load per stack all operating 5 KW/10	= .500 KW
Parasitic load per stack 100 watts/2	= .050 KW
Total	<u>.550 KW</u>

Specific reactant consumption - .806 lb/KW-hr
 Total mission power 200 hrs x .550 x 10 - 1100 KW
 Total reactant consumption .806 x 1100 - 886 lb
 Cryogenic tankage factor 0.4 x 886 - 354 lb
 Module reliability - .975691
 System reliability - mission - .999283
 fail-safe - .999419

Alternate Configuration #2



Weight of a single stack - 35 cell/stack module	= 67 lb
Load per stack all operating 5 KW/8	= .625 KW
Parasitic load per stack	= <u>.100 KW</u>
Total	.725 KW

Specific fuel consumption - .825 lb/KW-hr
 Total mission power 200 hrs x .725 x 8 - 1160 KW-hr
 Reactant consumption 1160 x .825 - 960 lb
 Cryogenic tankage factor 0.40 x 960 - 384 lb
 Module reliability - .980698
 System reliability - mission - .999618
 fail-safe - .999992

<u>Summary</u>	<u>Total System Wt</u>	<u>Reliability</u>		<u>Modules</u>
		<u>Mission</u>	<u>Fail-Safe</u>	
Base Line	1895 lb	.999893	.999990	4
Alternate #1	1820 lb	.999283	.999419	5
Alternate #2	1880 lb	.999618	.999992	8

Cost effectiveness is a stand-off.

October 1, 1970



Table XII

VOLTAGE REGULATION STUDY

<u>Case No.</u>	<u>Description</u>	<u>Pres.</u>	<u>Reg.</u>	<u>P-R Voltage</u>	<u>25%-R Voltage</u>	<u>Ave System Power</u>	<u>No. Mods for Ave Power</u>	<u>Stack Load Ave Power</u>	<u>SFC @ Ave Power lb/KW-hr</u>	<u>System Wt.</u>	<u>ASF @ Rated</u>
I	2 stks/mod, 34 cells/stk	Hi	No	30.6±3.4 ±11.1%	29.7±2.5 ±8.5%	5 KW	2	1.3 KW	.826	1612	135
II	3 stks/mod, 32 cells/stk	Hi	No	29.6±2.1 ±7.1%	29.0±1.5 ±5.2%	5 KW	2	.870	.802	1754	90
III	2 stks/mod, 35 cells/stk	Hi	Yes	28±1.4 ±5%	-	5 KW	2	1.44	.83	1817	140
IV	3 stks/mod, 35 cells/stk	Lo	No	31.0±3.7 ±12%	30±2.7 ±9%	5 KW	2	.870	.84	1848	90
V	3 stks/mod, 35 cells/stk	Lo	Yes	28.0±1.4 ±5%	-	5 KW	2	.963	.85	2054	100
VI	2 stks/mod, 41 cells/stk	Lo	Yes	28.0±1.4 ±5%	-	5 KW	2	1.44	.885	1887	150

Table XIII
HIGH VOLTAGE TRADE STUDY

<u>Module Rating</u>	<u>Configuration</u>	<u>Nominal Voltage VDC</u>	<u>Module Wt. lb</u>	<u>Specific Wt. lb/KW</u>	<u>Module Size in.</u>	<u>React. Cons. lb/KW-hr</u>	<u>Reliability 200 hr Mission</u>	<u>Heat Rejection @ Rated - Btu/hr</u>
<u>High Pressure (w/o voltage regulator)</u>								
<u>4 KW</u>	2 stks - 32 cells/stk - 0.70 ft ² /cell	29, 58, 116	110	27.5	13"D x 30"L	.885	.9765	10,600
	2 stks - 32 multi-volt cells/stk - 0.70 ft ² /cell	232	110	27.5	13"D x 30"L	.885	.9765	10,600
<u>6 KW</u>	3 stks - 32 cells/stk - 0.70 ft ² /cell	29, 58, 174	160	26.7	13"D x 44"L	.885	.9722	15,400
	3 stks - 40 cells/stk - 0.70 ft ² /cell	232	182	30.3	13"D x 53"L	.860	.9691	14,200
	2 stks - 65 cells/stk - 0.70 ft ² /cell	232	175	29.1	13"D x 54"L	.847	.9678	13,900
	2 stks - 32 multi-volt cells/stk - 1.11 ft ² /cell	232	185	30.9	20"D x 30"L	.885	.9765	15,400
<u>8 KW</u>	4 stks - 32 cells/stk - 0.70 ft ² /cell	29, 58, 116, 232	204	25.5	13"D x 60"L	.885	.9680	20,600
<u>Low Pressure (w/voltage regulator)</u>								
<u>4 KW</u>	2 stks - 38 cells/stk - 0.70 ft ² /cell	29, 58, 116	137	34.2	13"D x 34"L	1.05	.9742	14,700
	2 stks - 38 multi-volt cells/stk - 0.70 ft ² /cell	232	137	34.2	13"D x 34"L	1.05	.9742	14,700
<u>6 KW</u>	3 stks - 38 cells/stk - 0.70 ft ² /cell	29, 58, 174	194	32.4	13"D x 52"L	1.05	.9692	22,100
	3 stks - 47 cells/stk - 0.70 ft ² /cell	232	221	36.8	13"D x 59"L	.945	.9659	17,900
	2 stks - 70 cells/stk - 0.70 ft ² /cell	232	203	33.9	13"D x 57"L	.945	.9658	17,900
	2 stks - 37 multi-volt cells/stk - 1.08 ft ² /cell	232	185	30.8	20"D x 34"L	1.05	.9745	22,100
<u>8 KW</u>	4 stks - 38 cells/stk - 0.70 ft ² /cell	29, 58, 116, 232	252	31.5	13"D x 68"L	1.05	.9642	29,500

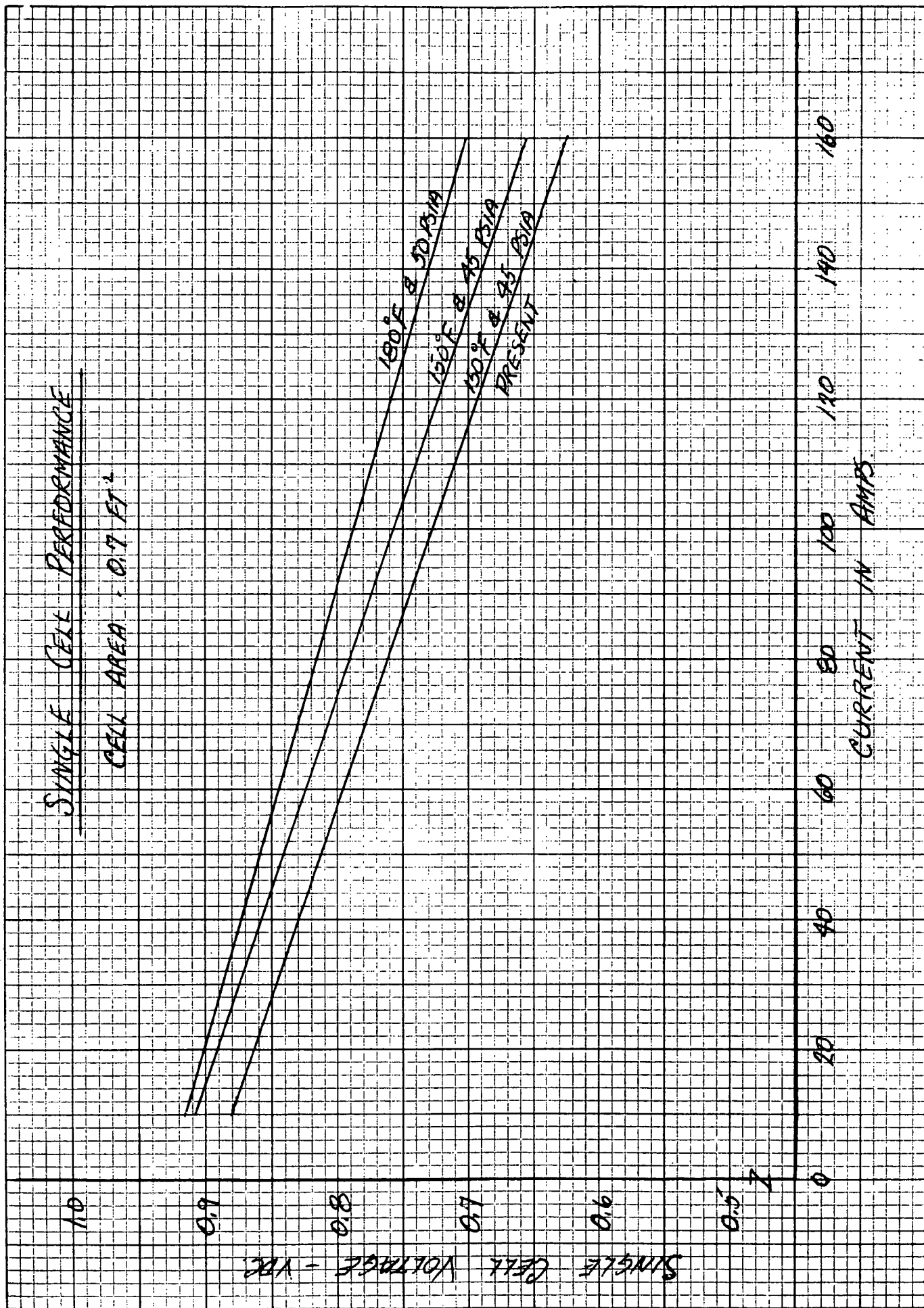


Figure 49.

6/14/71

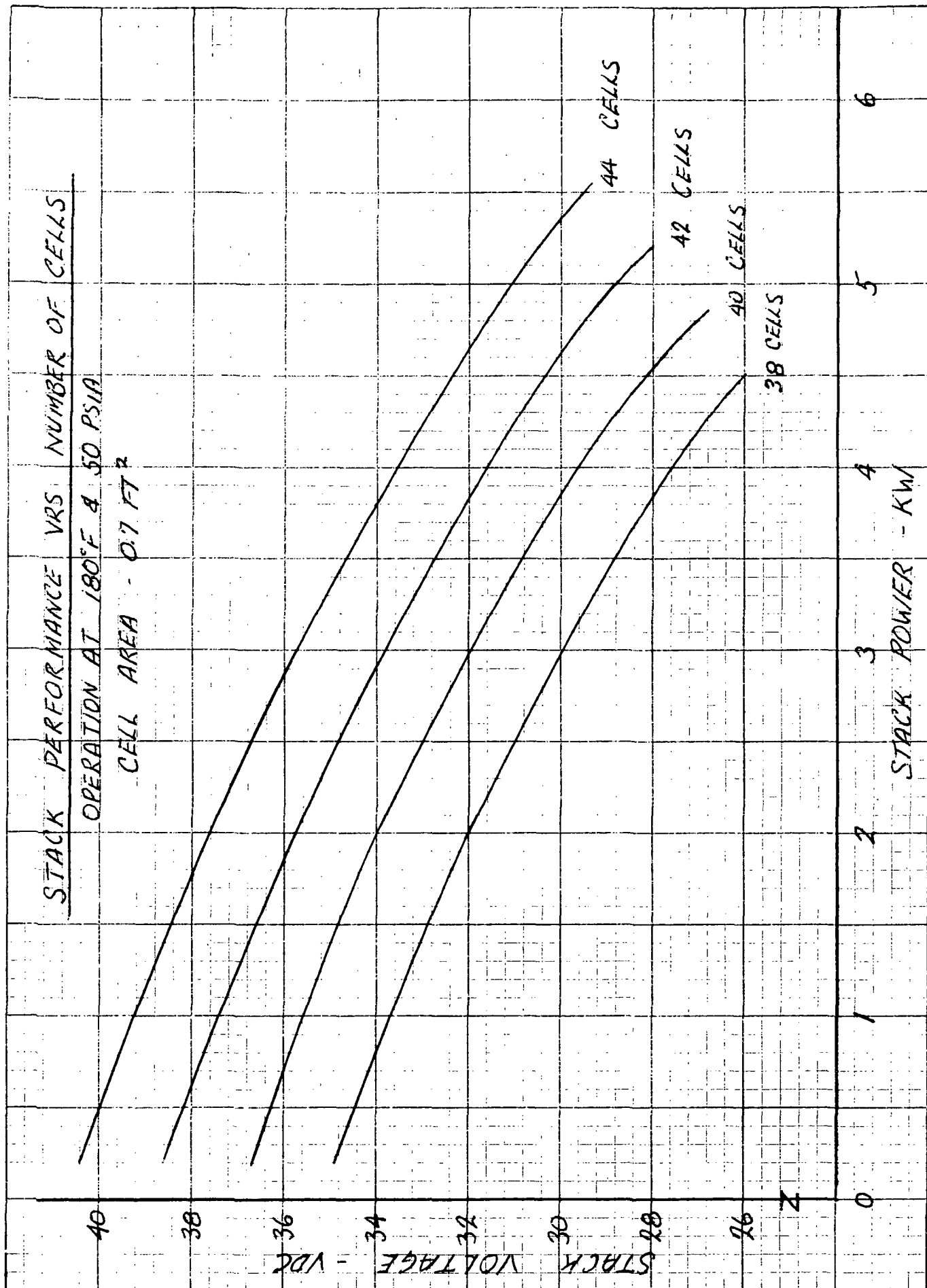
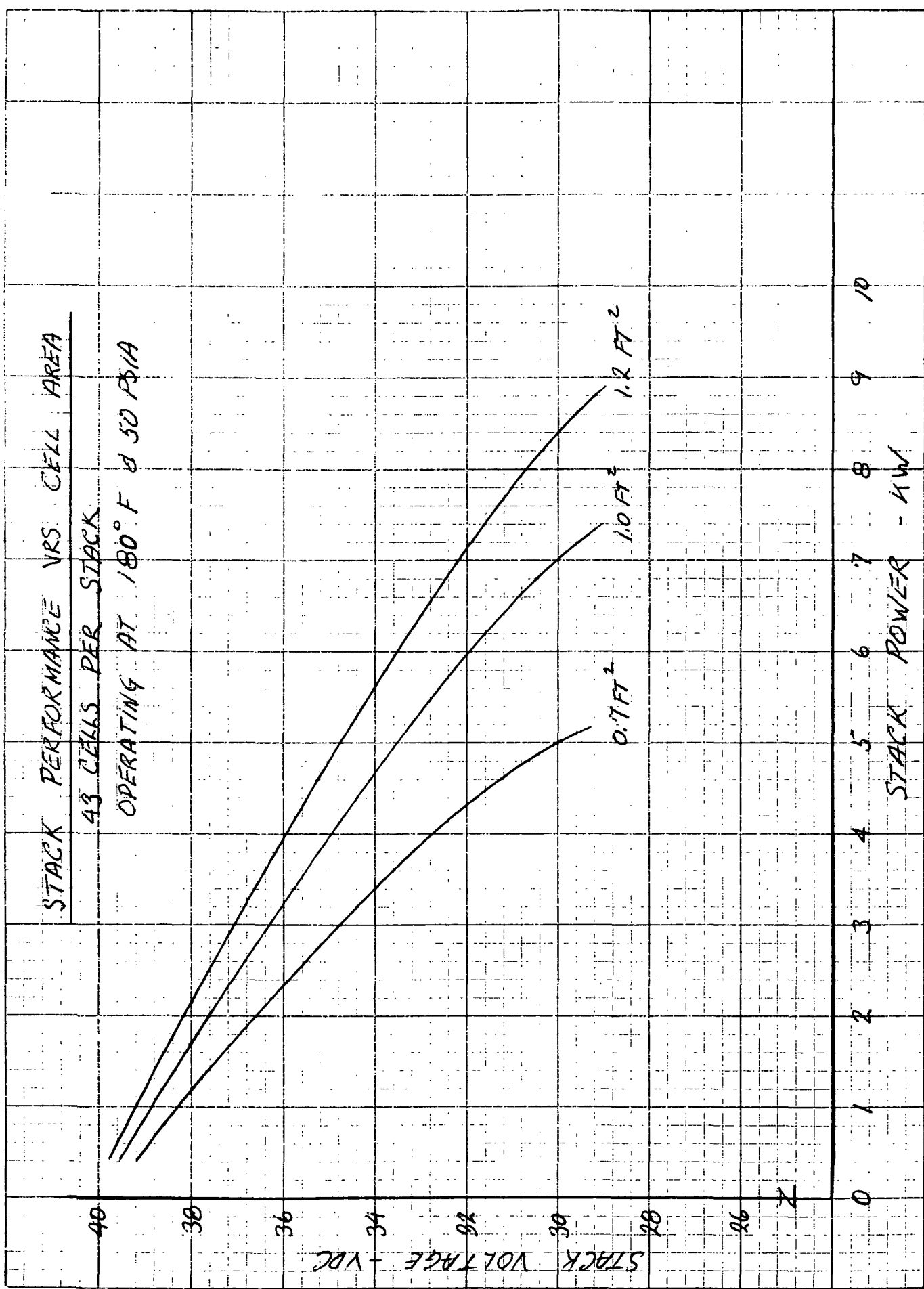


Figure 50.

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LEC



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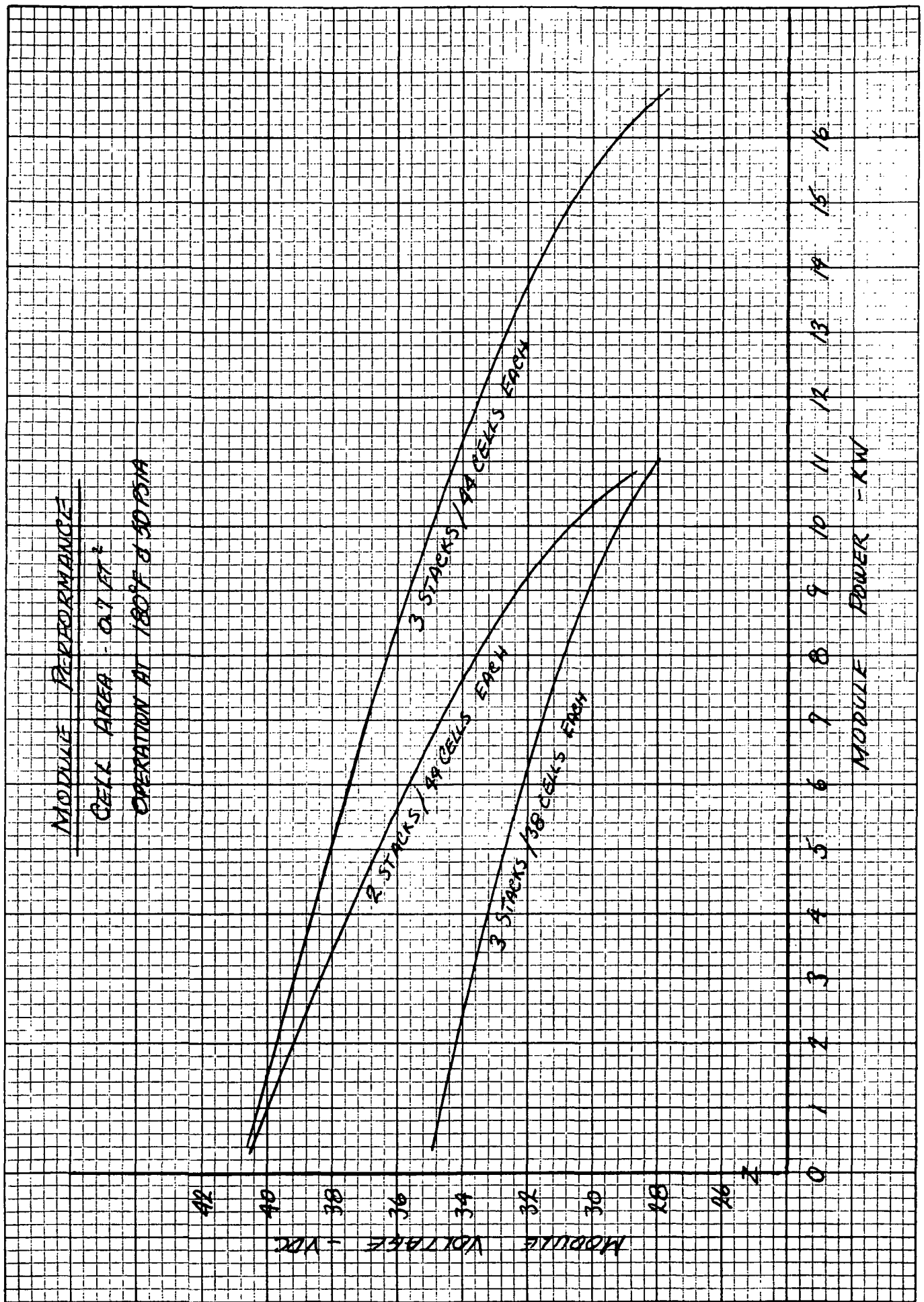


Figure 52.

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LEC

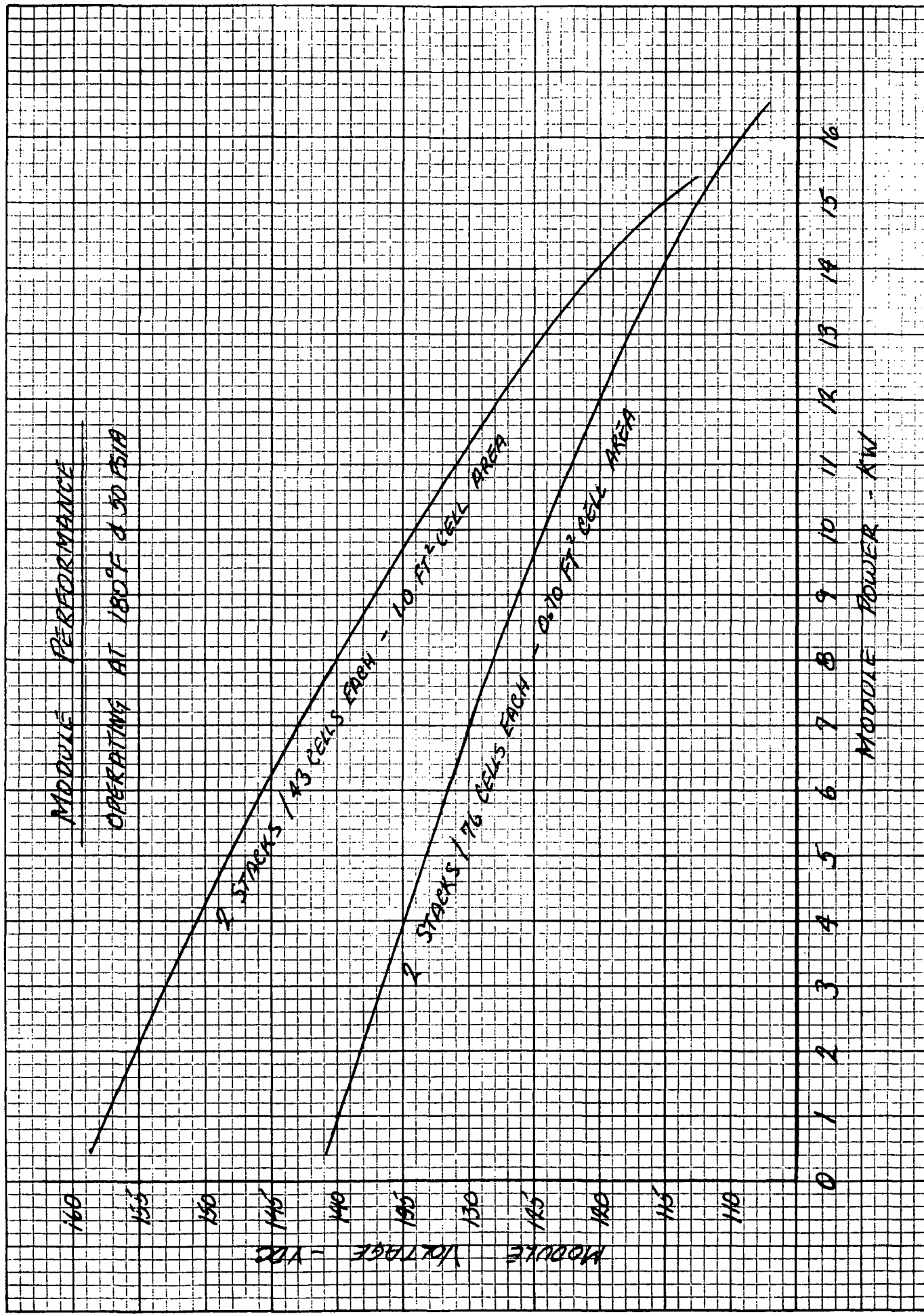


Table XIV

Summary

Module Sizing Study

Power Rating	Voltage Range	Module Configuration	Module Weight	Module Size	Rated ASF/VDC	Peak ASF/VDC
7/10 KW	29-35	Cell area 0.70 ft ² 3 stks/38 cells ea.	184 lb	13" dia 52" lg	106/.826	163/.770
7/10 KW	30-40	Cell area 0.70 ft ² 2 stks/44 cells ea.	141 lb	13" dia 39" lg	144/.788	233/.698
7/15 KW	30-40	Cell area 0.70 ft ² 3 stks/44 cells ea.	202 lb	13" dia 55" lg	90/.841	233/.698
7/15 KW	110-140	Cell area 0.70/2ft ² 2 stks/76 cells ea.	214 lb	13" dia 70" lg	77/.855	190/.740
7/15 KW	110-160	Cell area 1.0/2ft ² 2 stks/43 cells ea.	189 lb	15" dia 39" lg	98/.830	261/.672



6. MANAGEMENT TASKS

6.1 General

Overall management and financial control of the program was conducted under this task. This included monitoring and revision of the program plan, task support plans and schedules, NASA coordination, configuration control, monitoring the resources control plan, and generation of program documentation.

6.2 Major Program Documents

The following major documents were issued in support of this program:

- GE Document SPR-001, Fuel Cell Technology Program Plan
- 002, Reliability Program Plan
 - 003, Work Breakdown Structure
 - 005, Electromagnetic Interference (EMI) Plan
 - 007, Small Stack Test Plan
 - 008, Component Test Plan
 - 009, System Safety Plan
 - 011, Hazard Identification and Index Report (Included in Monthly Report No. 2)
 - 012, Mass Properties Control Report (Included in Monthly Report No. 3)
 - 013, NASA/Contractor Quarterly Review and Engineering Model Design Review Agenda (28 October 1970 Review)
 - 014, Contract End Item Specification - Design and Performance Base Line for Engineering Model No. 1
 - 015, Phase B Contractors Liaison Meeting, NAR/GE, MDAC/GE (13 October 1970)
 - 017, NASA/Contractor Quarterly Review and Engineering Model Design Review (28 October 1970 Review)
 - 018, Proposed Revisions to Fuel Cell Technology Program Plan
 - 019, Failure Analysis Report on Buildup No. 1
 - 021, Fuel Cell Module Failure Mode and Effect Analysis
 - 024, Proposed Revisions to Fuel Cell Technology Plan
 - 026, Technology Advancement and Exploitation Report
 - 027, NASA/Contractor Meeting Minutes (18 - 19 February 1971)
 - 031, Proposed Revisions to Fuel Cell Technology Program Plan
 - 033, Fuel Cell Technology Program Plan Revisions per Amend./Mod. No. 2S
 - 036, Single Cell and Small Stack Test Report - Buildup No. 2
 - 039, Single Cell and Small Stack Test Report - Buildup No. 3/3A
 - 042, Single Cell and Small Stack Test Report - Buildup No. 4 and 5/5A

GE Document SPR-046, Contract Summary Report
-048, Component/Subsystems Test Report
-049, Failure Analysis Summary Report

7. COMPLEMENTARY ENGINEERING

This area included studies supporting the overall fuel cell technology program development.

7.1 Reliability

Two major efforts were undertaken relative to project reliability. First was the issuance of a fuel cell module failure mode and effect analysis (GE document SPR-021). This analysis, of necessity, made use of many assumptions relative to the orbiter configuration. However, it should provide a base for understanding inter-relationships between the fuel cell system and the various orbiter subsystems.

The second task was in the collection and analysis of fuel cell data relative to the small stack failures and proposed corrective actions. The failure analysis and corrective action plan for each failure was covered in the final report for each unit.

Because of the diverting of man power to corrective action plans, the final reliability report was deleted from this contract.

7.2 Hazard Identification

A hazard identification and index report (included in GE document SPR-011) was generated. This analysis revealed only one Class A (system or personnel loss) interrelationship between the fuel cell system and the orbiter. This Class A condition considered only a single orbiter coolant loop servicing all fuel cell modules. Redundant loops for each module or each pair of modules would eliminate the Class A item.

7.3 Mass Properties Control Report Update

A mass properties control report (included in GE document SPR-012) was issued earlier in the contract. An updated version is presented in the following section.

MASS PROPERTIES CONTROL REPORT (Revised September 8, 1971)Introduction

This mass properties report is prepared using NASA document SP-6004, Mass Properties Standard, as a guide. The component weights shown are those planned for the base line design configuration of EM-1 which is sized for operation on low-pressure reactants from the propulsion tanks. The major variances from the weight breakdown of GE Proposal DE-005 are shown and explained. EM-1 will not be flight weight optimized in all areas.

The detailed mass properties breakdown is based on the dry weights of components and the total wet constituents are summarized on Form 1.

The voltage regulator has been excluded from this report since trade-off studies are being conducted to evaluate the effects of widening the fuel cell voltage output tolerance to accommodate the inherent voltage limits of an unregulated power supply such that the regulator would not become an essential part of the Fuel Cell Power Supply module.

This report does not include data on the center of gravity and moments of inertia for the module and the components since the packaging arrangement for EM-1 is arbitrary and can be modified by subsequent design efforts to fit a particular set of installation requirements.

MASS PROPERTIES SUMMARY										
Code	Description	Specified Weight Base	Procuring Activity and GFE Changes	Revised Specified Weight Base	Current Weight	Changes Last to Current	Percentage Breakdown of Current Weight			Note No.
							Est	Calc	Act	
7.2	Power Source - Fuel Cell Module EM-1 (5 KW Rated) Coolant Fluid and Product Water	40-60 lb/KW (200-300 lb) -	None -	40-60 lb/KW (200-300 lb) -	30.01 lb/KW (150.08 lb) 21.30 lb	None -	24% 100%	10% 	66% 	(1)
<p>(1) Rated power is defined as the maximum sustained power at which thermal equilibrium and voltage regulation are maintained. The base line module design configuration for operation with the low-pressure reactants from the propulsion tanks and consisting of two 40-cell stacks is capable of a 5 KW output under this definition.</p>										
<p>Date: 9/8/71</p> <p>Form 1</p> <p>Report No. 2</p>										

DETAIL MASS PROPERTIES										
Code	Description	Class (E, C, A)	No. Req'd	Weight Each (lb)	Weight (lb) Code Generation			Proposal DE-005 Weight (lb)	Current vs. Proposal Weight Difference (lb)	Note No.
					First	Second	Third			
7.2	Power Source - Fuel Cell Module EM-1 (5 KW Rated)				150.08			125.72	+34.36	(1)
7.2.1	H ₂ Check Valve	Act.	2	.33		.66		-	+ .66	(2)
7.2.2	O ₂ Check Valve	Act.	1	.29		.29		-	+ .29	(3)
7.2.3	O ₂ Purge Valve	Act.	2	.47		.94		.45	+ .49	
7.2.4	H ₂ Purge Valve	Act.	2	.47		.94		.45	+ .49	
7.2.5	H ₂ Latching Solenoid Valve	Act.	1	1.33		1.33		.45	+ .88	
7.2.6	O ₂ Latching Solenoid Valve	Act.	1	1.33		1.33		.45	+ .88	
7.2.7	H ₂ O Latching Solenoid Valve	Act.	1	1.41		1.41		.90	+ .51	
7.2.8	H ₂ O Regulator	Est.	1	.60		.60		1.30	- .70	(4)
7.2.9	H ₂ Regulator	Act.	1	1.12		1.12		1.30	- .18	(5)
7.2.10	Temperature Control Valve	Act.	1	1.57		1.57		-	+ 1.57	
7.2.11	Power Junction Box									
7.2.12	Purge Timer and Electrical Controls	Est.	1	3.30		3.30		3.30	0.0	
7.2.13	Structures and Plumbing	Est.	-	2.30		2.30		2.20	+ .10	
7.2.14	Transducer	Act.	5	.23		1.15		.20	+ .95	
7.2.15	Absolute Pressure Switch	Est.	2	.20		.40		.20	+ .20	
7.2.16	Coolant Accumulator	Act.	1	2.64		2.64		.50	+ 2.14	
7.2.17	Coolant Pump	Act.	1	4.25		4.25		2.30	+ 1.95	
7.2.18	Heat Exchanger	Act.	1	1.26		1.26		1.20	+ .06	(6)
7.2.19	Fuel Cell Housing	Calc	1	14.11		14.11		12.00	+ 2.11	(7)
7.2.20	Fuel Cell Stack Assembly	Est/Calc/ Act.	2	55.24		110.48		98.52	+11.96	
Date: 9/8/71										
Form 2, sht 1 of 2										
Report No. 2										

DETAIL MASS PROPERTIES										
Code	Description	Class (E, C, A)	No. Req'd	Weight Each (lb)	Weight (lb) Code Generation			Proposal DE-005 Weight (lb)	Current vs. Proposal Weight Difference (lb)	Note No.
					First	Second	Third			
7.2.20.1	Anode End Frame	Act.	1	2.07			2.07	1.75	+ .32	
7.2.20.2	Cathode End Frame	Act.	1	2.07			2.07	1.75	+ .32	
7.2.20.3	Anode End Plate	Act.	1	.72			.72	1.75	-1.03	
7.2.20.4	Cathode End Plate	Act.	1	.72			.72	1.75	-1.03	
7.2.20.5	H ₂ O Separator and Fittings	Calc	Set	2.59			2.59	3.50	- .91	
7.2.20.6	Electrical Connections	Est./Act.	Set	.22			.22	.20	+ .02	
7.2.20.7	Piping (O ₂ , H ₂ , Coolant)	Est.	Set	.25			.25	.25	0.0	
7.2.20.8	Tie Rods, Nuts, Springs	Ext.	Set	.75			.75	.75	0.0	
7.2.20.9	O ₂ Dacron Wicks	Calc	80	.0245			0.0	2.00	-2.00	(9)
7.2.20.10	O ₂ Spacer	Calc	39	.0742			2.89	1.40	+1.49	
7.2.20.11	O ₂ Frame and Screen and Wick Assembly	Act.	80	.18			14.40	9.92	+4.48	(10)
7.2.20.12	Cell Assembly	Act.	40	.714			28.56	24.24	+4.32	(11)
Date: 9/8/71										
Form 2, sht 2 of 2										
Report No. 2										

DETAIL MASS PROPERTIES

NOTES

- (1) Major differences between current and Proposal DE-005 weights are explained in notes below.
- (2) H₂ check valves not included in Proposal DE-005 weight.
- (3) O₂ check valve not included in Proposal DE-005 weight.
- (4) Temperature control valve not included in Proposal DE-005 weight since it was then assumed to be on the vehicle side of the interface.
- (5) Power junction box not included in Proposal DE-005 weight. The line contactors were assumed to be on the vehicle side of the interface in the original proposal. Contactors are now planned with EM-1 to be integrated with the automatic shutdown control and to provide access to electrical charging during the ground startup procedure. In the ultimate Space Shuttle installation, the Prime Contractors intend to include the contactors on the vehicle side of the interface.
- (6) The container assembly has increased in length to accommodate the necessary plumbing connections.
- (7) Stack assembly weights are further broken down, Form 2, sheet 2, with explanation for the differences.
- (8) O₂ dacron wicks now part of Item 7.2.20.11.
- (9) Material thickness was increased for additional structural rigidity.
- (10) Addition of wick pads for hydrogen reactant humidification and electrical tab compression buttons for ease of assembly.
- (11) The proposal weight was based on use of titanium alloy for the coolant cartridge; however, it is planned to use niobium until the titanium can be fully evaluated.

8. GLOSSARY OF TERMS

Solid Polymer Electrolyte (SPE) - Term synonymous with Ion Exchange Membrane in the General Electric Fuel Cell Technology where the sulfonic acid (SO_3^-) radicals of the electrolyte are chemically linked to the structure of a backbone polymer processed into a continuous sheet of material.

Membrane and Electrode Assembly (M and E) - Term used to identify the solid polymer electrolyte which has been equilibrated to the specified water content and with the anode and cathode catalytic electrode structures attached.

Water Content of the SPE - The amount of water added to the dry solid polymer electrolyte sheet expressed as a percentage of the dry weight.

Equilibration - The process by which the water is added to the dry SPE. The amount of water which the SPE will absorb is a function of the equilibration temperature.

Ion Exchange Capacity - The milliequivalents of sulfonic acid groups per gram of dry membrane.

Equivalent Weight of SPE - The reciprocal of the ion exchange capacity times 1000.

Delamination of SPE - Description of the failure mode of the SPE sheet where the polymer has locally blistered or separated at the center line of a cross-section of the polymer sheet.

Extruded/Skived SPE - Description of the process used to produce the polymer in sheet form. The extrusion process forces the polymer through a die under heat resulting in the formation of a continuous sheet of polymer material. The skived description results from the processing whereby the polymer is first molded into blocks and then sheets of polymer material are produced by slicing or skiving sections from the blocks.

Platinized SPE - The process whereby Pt ion is exchanged into membrane and then reduced to form very small particles dispersed throughout the SPE as a scavenger for hydrogen peroxide.

Hydrogen Peroxide Attack - Hydrogen peroxide is formed as an intermediate reaction at the cathode of an acid electrolyte fuel cell and at the anode from the O_2 diffusing through the SPE. The presence of platinum acts as a catalyst to reduce the H_2O_2 to water. The hydrogen peroxide is a very strong oxidizing agent and will attack weak links in the carbon-fluorine polymer chains degrading the polymer.

HF Release - A by-product of the degradation of the carbon-fluorine polymer is hydrofluorine acid (HF) which is leached out of the fuel cell with the product water.

Deep Discharge - A fuel cell activation procedure which consists of filling the anode side with hydrogen and the cathode side with an inert gas. An electrical load is then applied driving the cells down to zero volts. The low cathode voltage removes the attraction of the cation contaminants to the catalyst such that purging of the inert gas can remove them from the system. At voltages below 0.3 VDC, hydrogen will be deposited on the cathodes causing the reduction of any platinum oxides formed during the manufacturing processes.

Oxygen Takeover - Term applied to the storage condition of a fuel cell when oxygen is present in both sides of the cell. This condition occurs during a shut-down and deactivation of a unit by shutting off the hydrogen inlet valve and allowing the normal gas diffusion across the SPE to consume the residual hydrogen in the very small volumes at the anode and replacing it with oxygen which diffuses from the large oxygen volume. In this mode a fuel cell can be stored with no further reactant consumption.

Electrical Charge - This term is synonymous with Electrolysis Start and consists of applying a power supply to the fuel cell stack connected in a reversed polarity to fuel cell operation. Current is passed through the cells to electrolyze some of the water contained in the SPE so as to charge the reactant cavities with hydrogen and oxygen. In the case of the O₂ takeover type storage, the oxygen in the anode cavity is consumed by the evolving hydrogen at a controlled uniform rate. Then the anode cavity is filled to operating pressure with the evolved hydrogen.

Stop/Start Procedures - The optimum stop/start procedure for ground level operation is as follows:

To Stop:

1. Open switch or contactor to electrical load.
2. Close inlet hydrogen solenoid.
3. Turn off coolant pump.

In this condition the oxygen will diffuse through the SPE and consume the hydrogen in the anode compartment in a slow and uniform manner. When this occurs the unit is deactivated and can be stored indefinitely with no reactant consumption.

To Start:

1. Turn on the coolant pump.
2. Apply a reversed polarity power supply to electrolyze the cells.
3. When the oxygen has been consumed from the anode and the hydrogen pressure rises to 46 psia, open the hydrogen inlet solenoid and turn off the electrolysis power.
4. Close the switch or contactor to apply the electrical load.

The optimum stop/start procedure for in-orbit operation is as follows:

To Stop:

Same as ground operations.

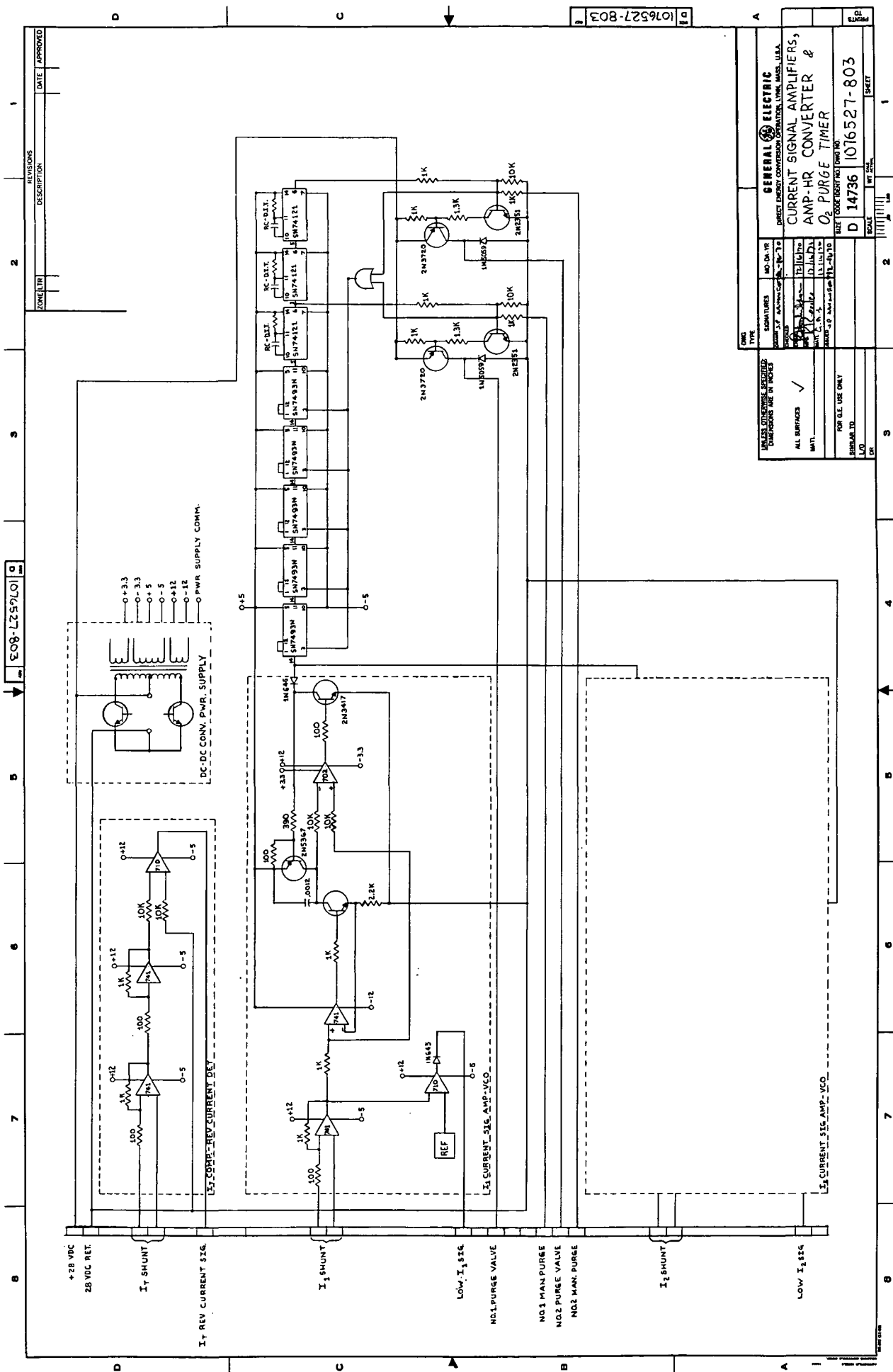
To Start:

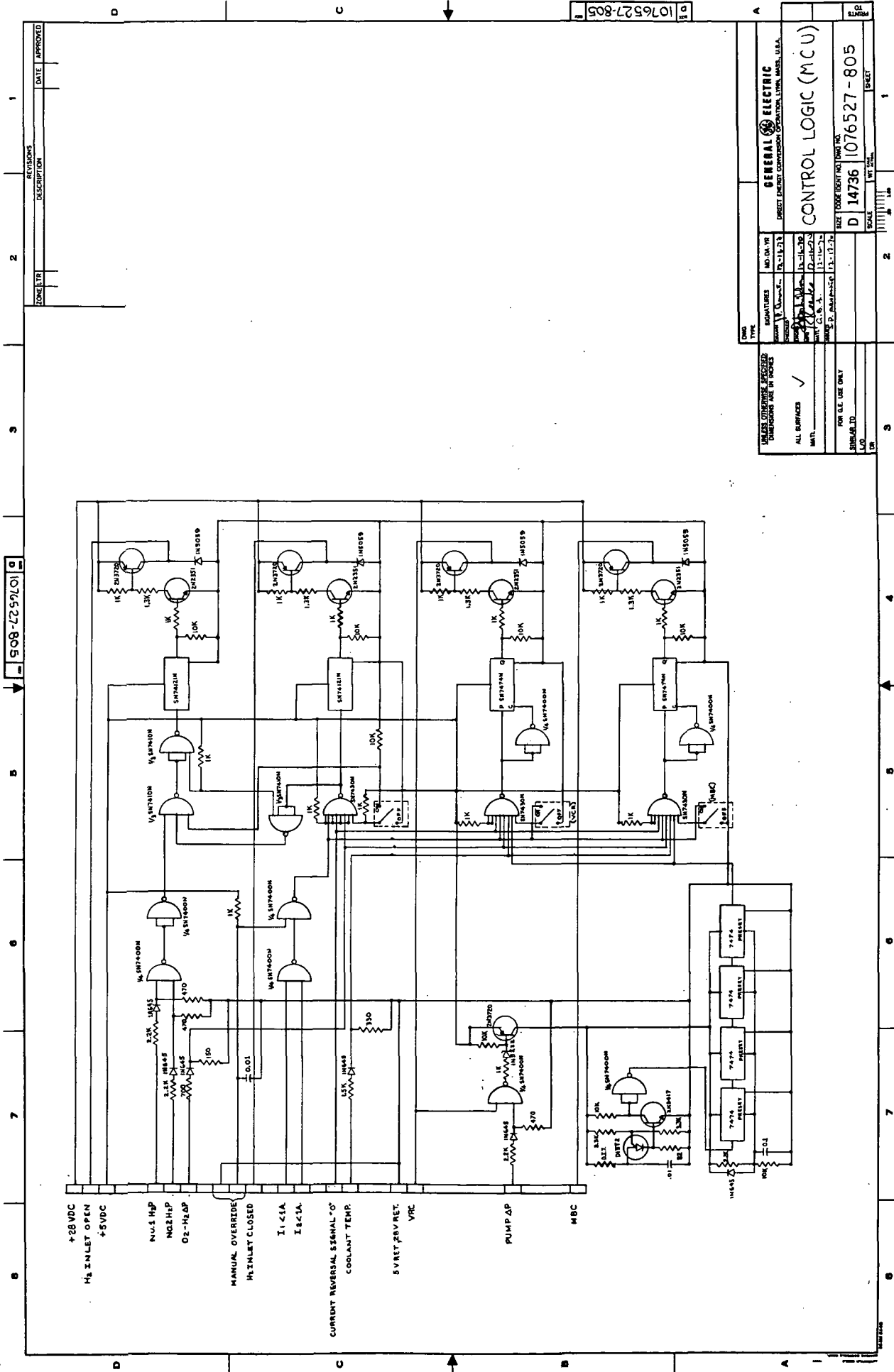
1. Turn on the coolant pump.
2. Open anode compartment to space vacuum momentarily.
3. Open the hydrogen inlet solenoid valve.
4. Close the switch or contactor to apply the electrical load.

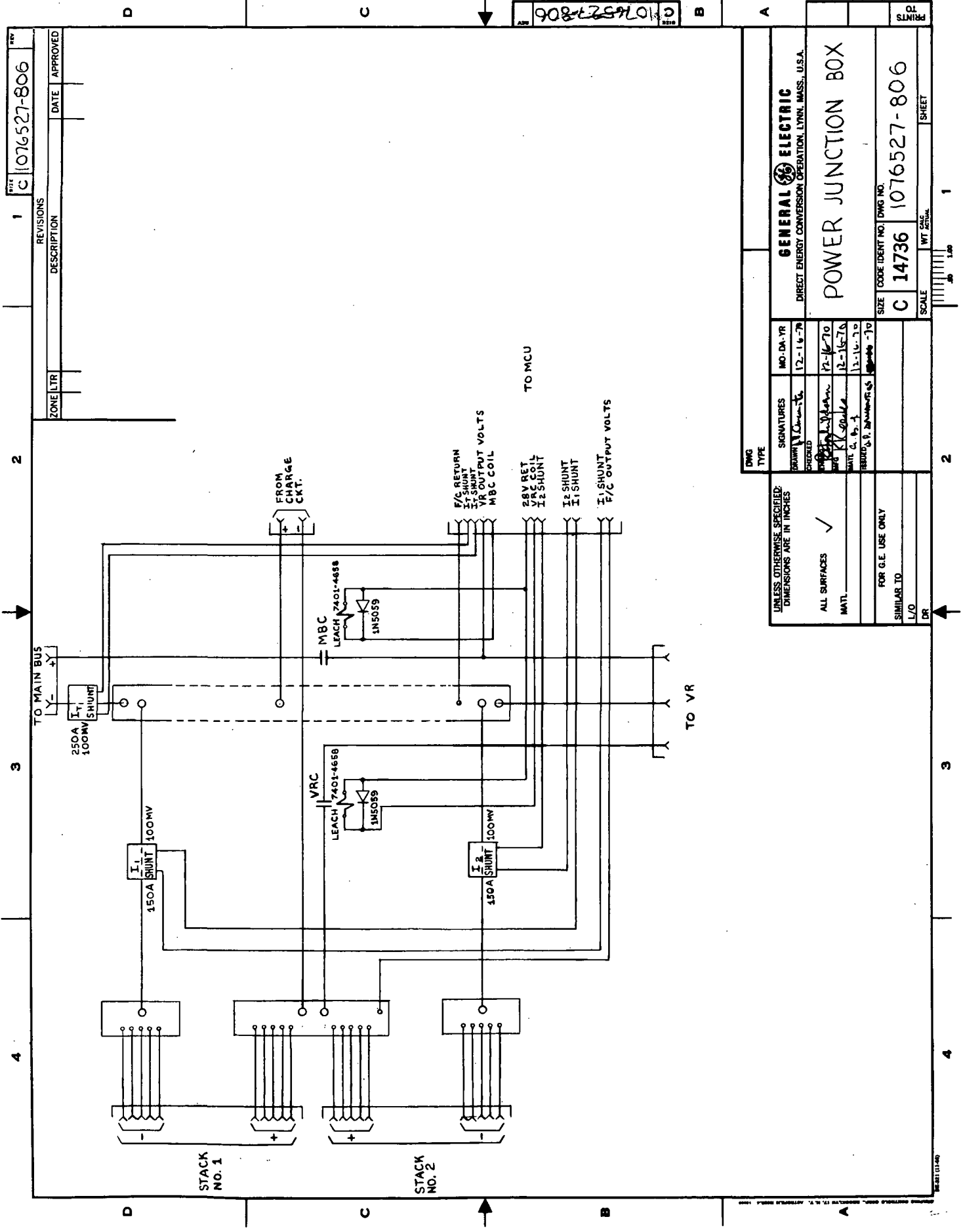
By using these procedures there are no inert gases required. Only a power supply is needed while on the ground and only the readily available vacuum for space operation.

APPENDIX

	<u>Page</u>
GE Drawing 1076527 -802	130
-803	131
-804	132
-805	133
-806	134
-807	135
-835	136
-751	137
-754	138
-842	139

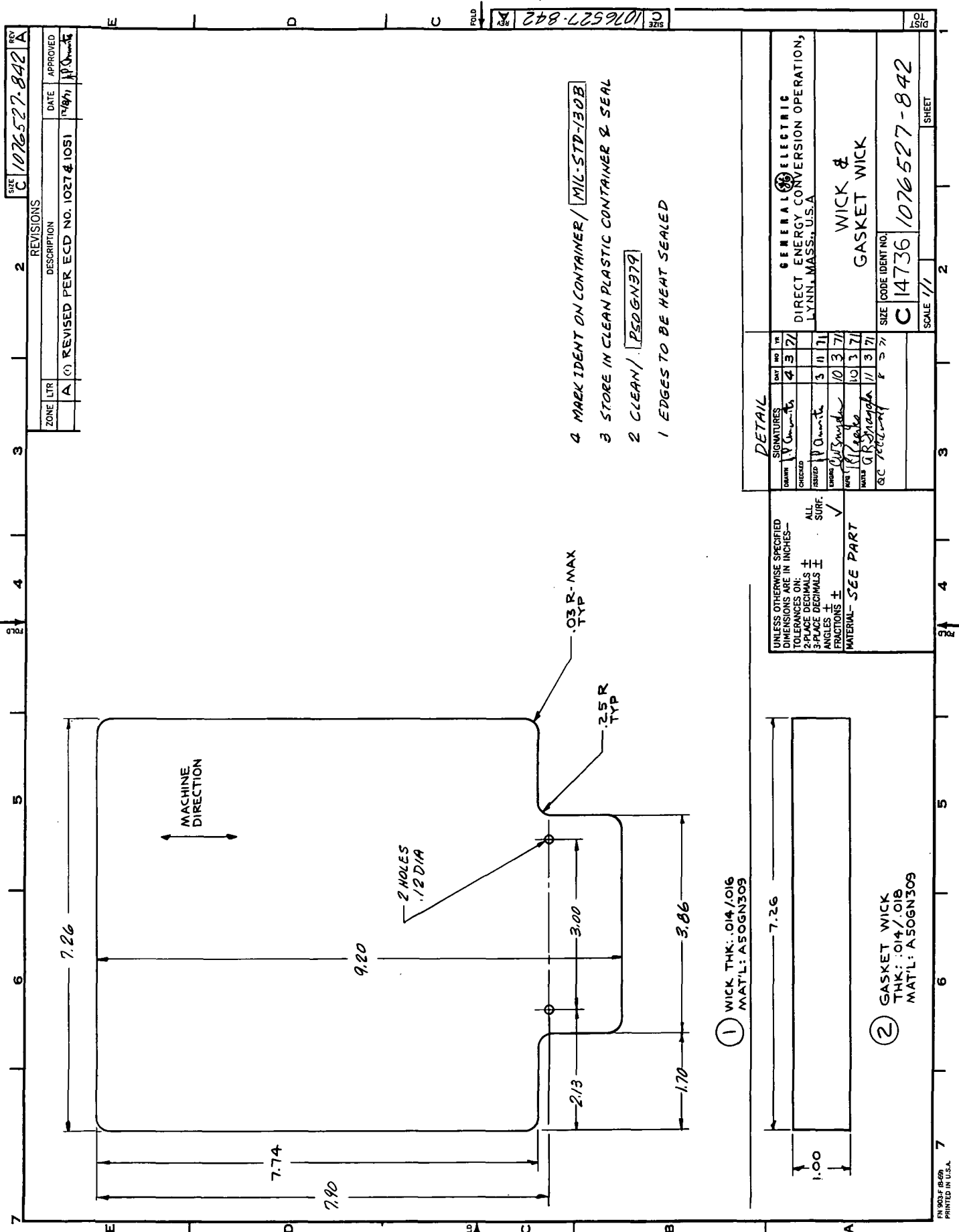






REV		C 1076527-806	
1		2	
ZONE LTR		DATE APPROVED	
DESCRIPTION			

GENERAL ELECTRIC		DIRECT ENERGY CONVERSION OPERATION, LYNN, MASS., U.S.A.	
POWER JUNCTION BOX			
SIZE	CODE IDENT NO.	DWG NO.	
C 14736	1076527-806		
SCALE	WT. CALC.	SHEET	1



SIZE	C	1076527-842	REV	A
2		REVISIONS		
ZONE	LTR	DATE	APPROVED	
A	(1)	REVISED PER ECD NO. 1027 & 1051	12/19/71 J. P. O'Quinn	

- 4 MARK IDENT ON CONTAINER/ MIL-STD-130B
- 3 STORE IN CLEAN PLASTIC CONTAINER & SEAL
- 2 CLEAN/ P50GN379
- 1 EDGES TO BE HEAT SEALED

DETAIL		SIGNATURES		DATE	REV
DRAWN	W. O'Quinn	4	3	71	
CHECKED					
DESIGNED	W. O'Quinn	3	11	71	
ENGINEER	W. O'Quinn	10	3	71	
MANUFACTURED BY	W. O'Quinn	10	3	71	
QC	W. O'Quinn	11	3	71	
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES— TOLERANCES ON: 2-PLACE DECIMALS ± 3-PLACE DECIMALS ± ANGLES ± FRACTIONS ± MATERIAL—SEE PART		GENERAL ELECTRIC DIRECT ENERGY CONVERSION OPERATION, LYNN, MASS., U.S.A.			
GASKET WICK THK: .014/.018 MAT'L: A50GN309		WICK & GASKET WICK		SIZE CODE IDENT NO. C 14736	
1 WICK THK: .014/.018 MAT'L: A50GN309		2		SCALE 1/1	
2 GASKET WICK THK: .014/.018 MAT'L: A50GN309		3		SHEET	